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CALIFORNIA WIND ENERGY RESOURCE MODELING AND MEASUREMENT: Measurement Program Final Report

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PIER PROJECT TASK REPORT

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Abstract

This report presents the results of a wind resource measurement study conducted on behalf of the California Energy Commission by AWS Truewind for five focus areas in California. The objective of the Measurement Program was to collect high-quality data at heights relevant to modern wind turbines. Data was collected from four tall tower locations and seven sodar sites in California. The analysis period covered in this report is from April 2004 to July 2005. A number of important wind characteristics are presented, including mean wind speed, wind shear, prevailing wind direction, and diurnal speed distributions. Long-term speed estimates were produced for the tall tower locations and sodar locations, when appropriate, through a comparison with regional meteorological reference stations.

Keywords

Wind measurement, tall-tower, sodar, wind speed, wind shear, diurnal wind distribution

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards funds to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
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- Energy-Related Environmental Research
- Strategic Energy Research

What follows is task report for the *California Wind Energy Resource Modeling and Measurement Project*, Contract Number 500-03-006, conducted by AWS Truewind, LLC. The report is entitled *California Wind Energy Resource Modeling and Measurement--Measurement Program Final Report*. This project contributes to the Renewable Energy program area.

For more information on the PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/pier/index.html or contract the Commission's Publications Unit at 916-654-5200.

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1.0 Introduction

This report presents the results of a wind resource measurement study conducted on behalf of the California Energy Commission (Energy Commission) by AWS Truewind for five focus areas in California (Figure 1**)**. The objective of the Measurement Program was to collect high-quality data at heights relevant to modern wind turbines. The data was used to improve boundary layer modeling, validate high-resolution modeling for the five focus areas, and enhance the accuracy of model estimates elsewhere in the state.

Data was collected from four tall tower locations and seven sodar sites in California. The analysis period covered in this report is from April 2004 to July 2005. A number of important wind characteristics are presented, including mean wind speed, wind shear, prevailing wind direction, and diurnal speed distributions. Long-term speed estimates were produced for the tall tower locations and sodar locations, when appropriate, through a comparison with regional meteorological reference stations.

Since the tall tower measurements were concurrent, they are discussed collectively. The sodar measurements were conducted in stages and are therefore discussed independently.

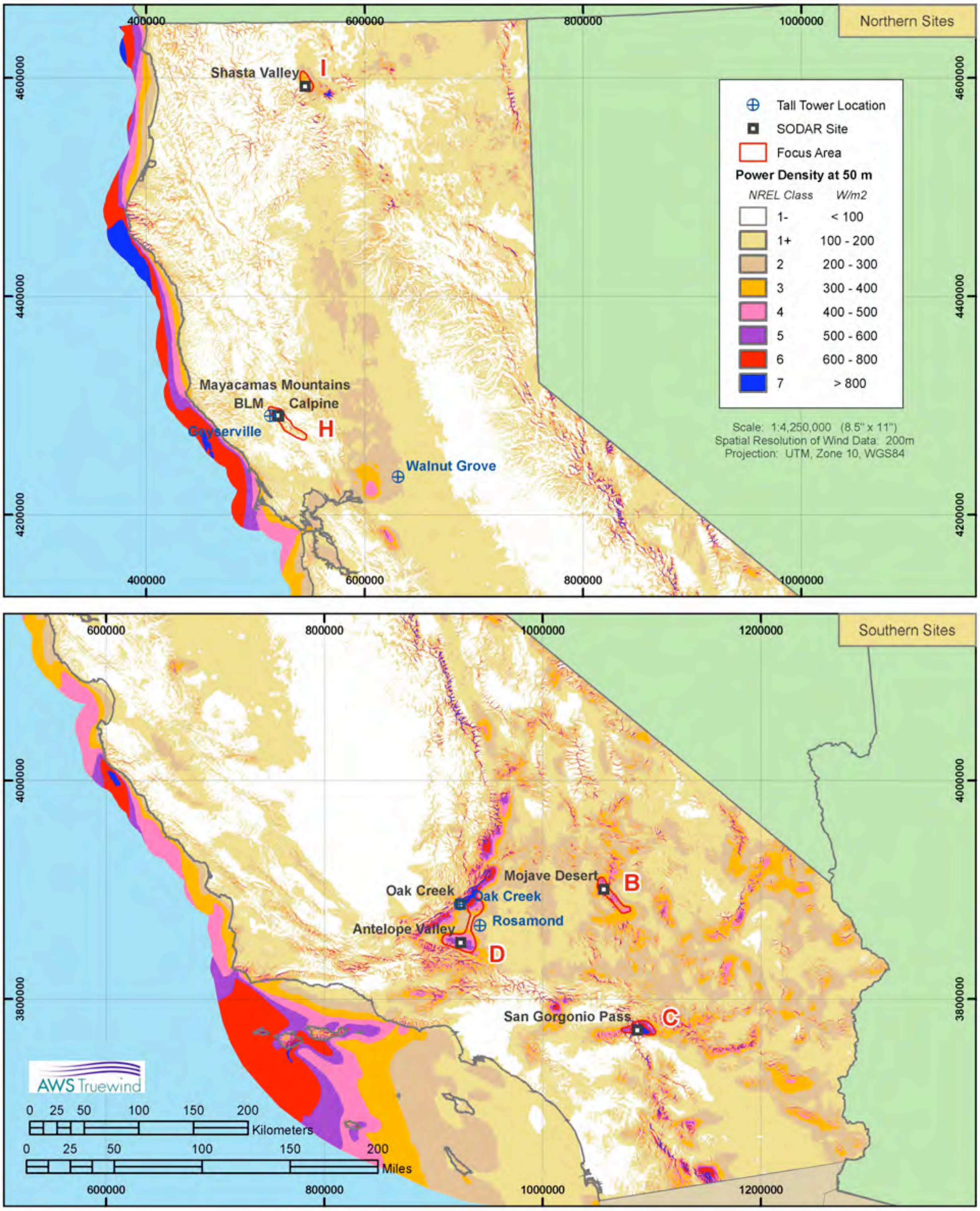

Figure 1: Overview of Focus Areas and Measurement Sites

2.0 Tall Tower Campaign

2.1 Site Descriptions

Two communication towers in north-central California (Transtower and Geyserville) and two in southern California (Oak Creek and Rosamond) were instrumented at three levels to collect wind speed and direction data. Figure 2 contains a map showing the monitoring site locations. Low-level temperature data were also collected at each site, with one tower in each region having an additional temperature sensor mounted at the top wind speed monitoring level. In addition to the knowledge of the wind characteristics, observing the vertical temperature profile is vital for further understanding boundary layer climatology. Table 28 contains detailed information about the anemometry mounted on each tower.

Oak Creek

The Oak Creek site is located in mountainous terrain about 15 km southeast of Tehachapi, California and about 30 km west-northwest of Edwards Air Force Base. The latitude / longitude coordinates are 35^{o} 2’ 3.5” N and 118^{o} 20’ 48.8” W. The site elevation is 1301 m. Wind monitoring equipment was mounted on a 91.5 m guyed-lattice tower and officially commissioned on 26 April 2004. Wind speed and direction data were collected at 88.4 m, 70.1 m, and 52.7 m. Temperature data were collected at 87 m and 10 m. The groundcover is typified by low, sparse shrubbery and there are numerous wind turbines and wind monitoring towers in the vicinity.

Rosamond

The Rosamond site is located in a flat desert plain about 1.5 km west of Edwards Air Force Base and about 25 km southeast of Oak Creek. The latitude / longitude coordinates are 34^{o} 51’ 3.2” N and 118^{o} 9’ 25.4” W. The site elevation is 703 m. Wind monitoring equipment was mounted on a 145 m guyed-lattice tower and officially commissioned on 2 July 2004. Wind speed and direction data were collected at 109.7 m, 76.8 m, and 44.8 m. Temperature data were collected at 5 m. The surrounding area is generally flat with few surface features.

Transtower

The Transtower site is located in a flat, low-lying river delta about 37 km south of Sacramento, California and about 38 km north-northwest of Stockton, California. The latitude / longitude coordinates are 38^{o} 14’ 49.4” N and 121^{o} 30’ 5.8” W. The site elevation is 6 m. Wind monitoring equipment was mounted on a 472 m guyed-lattice tower and officially commissioned on 31 July 2004. Wind speed and direction data were collected at 111.3 m, 84.7 m, and 46.1 m. Due to the large tower face width and relatively short instrument booms, a directionally dependent correction factor was applied to data from each anemometer to minimize tower effects. Temperature data

were collected at 112 m and 10 m. The surrounding area is flat with low trees and shrubbery. There are also some small buildings and satellite dishes in the vicinity.
Geyserville

The Geyserville site is located on a mountain ridge 0.5 km southeast of Geyser Peak, about 37 km north-northwest of Santa Rosa, California, and about 13 km northwest of Mount St. Helena. The latitude / longitude coordinates are 38^o 45' 43.9" N and 122^o 50' 28.0" W. The site elevation is 977 m. Wind monitoring equipment was mounted on a 61 m guyed-lattice tower and officially commissioned on 1 June 2004. Wind speed and direction data were collected at 60.1 m, 43.9 m, and 29.3 m. Temperature data were collected at 5 m. The terrain has a steep northwest to southeast gradient and groundcover consists mostly of 1 m shrubbery and a few low conifers.

2.2 Tall Tower Data Summary

All of the monitoring site raw data were collected using NRG Symphonie loggers and transferred to AWS Truewind via telephone and e-mail every three days. The data were converted according to the sensor calibration information provided and subsequently validated to ensure consistency among observations and to check for possible icing conditions during the cold season.

Table 29 summarizes all of the important wind characteristics observed at the sites, including mean wind speed, data recovery, mean wind shear, and turbulence intensity. Also among the statistics reported is the wind power density; a measure that provides a truer indication of a site's wind energy potential than the wind speed alone because it combines the effect of a site's wind speed frequency distribution with temporal variations in air density.

Average WPD is defined as the wind power available per unit area swept by a wind turbine's blades and is given by the following equation:

$$\textit{Average WPD} = \frac{1}{2n}\sum_{i=1}^{n}\rho \times v_i^{\,3} \ \ \mathbf{(W/m^2)}$$

where

n = the number of 10-minute records in the averaging interval;
ρ = the air density (kg/m^3); and
v_i^3 = the cube of the wind speed (m/s) at the ith 10-minute average record.

The mean wind shear – an indication of the change in wind speed with height – at each site was computed from concurrent valid records from the top two monitoring levels, and including only upper-level wind speeds greater than 4 m/s – the minimum speed required for energy production. Three of the four sites had turbulence intensity values between 0.095 and 0.114. Only Oak Creek had a significantly higher value at 0.152.

The Weibull distribution is an analytical probability function that can be used to describe the wind speed frequency distribution, or number of observations at specific wind speed values. It has two adjustable parameters (A and k) that enable it to fit a wide range of probability density functions. A is a scale parameter related to the mean wind speed while k controls the shape of the Weibull distribution. Values of k typically range from 1 to 3.5, the higher values indicating a narrower distribution.

Throughout the year, the mean air density varies directly with the ambient air temperature. This is an important characteristic to consider because the amount of energy produced by a wind turbine for a given wind speed is a function of the air density. A 10 % increase or decrease in air density can change the output of a wind turbine by nearly the same percentage. At each site, an energy-weighted annual air density was calculated where the weight was proportional to the energy content of the wind. The values ranged between 1.057 kg/m^3 and 1.221 kg/m^3 and are highly sensitive to site elevation.

The prevailing wind directions are concentrated and site-specific and are dependent on the nearby terrain. The wind roses are further detailed in the next section.

2.3 Monthly, Diurnal, and Directional Distributions

Table 30 contains the monthly mean wind speeds for the respective monitoring periods. Except for Geyserville, the highest wind speeds were observed during the late spring and summer months. This is caused by the large continental/marine temperature and pressure gradients that develop during the spring and summer months when the strongest solar heating occurs. Typically, the sea breeze is a small-scale meteorological phenomenon driven by differential heating between continental and marine air masses. Solar heating is the catalyst and since continental air masses warm (and cool) more quickly than marine air masses, a temperature and pressure gradient sets up between the land and sea, thereby increasing the wind speeds. However, in California, the sea breeze effects reach well into the interior because the offshore environment is controlled by a cold-water current that results in sea surface temperatures between 10^{o}C and 20^{o}C throughout the year. Conversely, inland temperatures often reach well above 30^{o}C during the warm season. This large temperature gradient forces cooler, more stable marine air through gaps in the coastal mountains into interior regions. Areas where this occurs often experience very strong, persistent winds.

Geyserville – being located on an inland ridge – is not as strongly affected by the sea breeze. Instead, the annual climate is controlled by the larger scale temperature and pressure gradients that are greatest during the colder months. This is evident by the strongest winds being observed from November through March.

Figure 3 presents each site's diurnal wind speed distribution. The distributions indicate the magnitude of the sea breeze effects at each monitoring site. Increasing wind speeds between the late morning and mid- to late afternoon hours are observed at all sites. Rosamond is the most strongly affected by the sea breeze because the peak daily winds are observed at around 4 PM before they drop sharply with the decrease in daytime heating. The other three sites experience nighttime wind speed maxima that are related to boundary layer stabilization and their respective elevations. This factor is detailed in the next section.

Figure 4 presents the wind rose for each respective site. The wind roses have little in common with one another as the nearby terrain strongly channels the prevailing wind directions.

The Oak Creek site is located southeast of Tehachapi; a northwest to southeast gap located 400 to 600 m below the surrounding terrain. Given the location of the tower with respect to Tehachapi and other mountains to the west, the energy producing winds blow almost exclusively (80%) from the northwest through the pass.

The Rosamond energy producing winds blow primarily from the southwest through westerly directions (over 80%) because of the tower location being between an 1800 m southwest to northeast ridge 25 km to the north and 1500 m west to east ridge about 50 km to the south. The winds are channeled from the ocean between the two ridges.

Transtower exhibits a wind rose that is also channeling related. The prevailing wind direction is from the west-southwest as the sea breeze flow is directed through the San Francisco and Grizzly Bays located to the west-southwest and between coastal hills. Secondary wind direction maxima are observed from the southeast and north-northwest. These directions correspond with the orientation of the ridgelines surrounding the central valley. Any winds not directly related to the sea breeze are channeled between those ridges.

At Geyserville, the wind direction is more variable than at the other sites. The prevailing energy-producing wind direction is from the north-northeast (roughly 30%). Generally, directional maxima are observed from the north and south, which coincides with the tower being located on the side of a north-northeast to south-southwest ridge.

The site-specific directional wind shear distributions show large fluctuations between sectors. However, this is misleading because each location experiences at least two-thirds (as high as 90% at Oak Creek) of its energy producing winds from a small portion of the wind rose. For this reason, the directional wind shear profile has limited importance.

The mean wind shear as a function of wind speed reveals an inverse relationship, as increasing winds tend to decrease the shear. While this is true throughout the entire profile at Oak Creek and Rosamond, Transtower and Geyserville suggest increasing wind shear up to wind speeds between 10 m/s and 12 m/s before the inverse relationship is observed. Table 31 contains the mean wind shear as a function of wind speed. Only wind speeds greater than 4 m/s are included since this is the typical cut-in speed for most commercial wind turbine models.

2.4 Vertical Temperature Profile Effects

A stable layer is one where the temperature increases with height and is characterized by stratified air and little vertical mixing. Conversely, an unstable air mass has the reverse temperature profile and induces a well-mixed environment where stronger winds from aloft are vertically mixed to the surface. Typically, under stable conditions, a shallow boundary layer exists because frictional effects from the Earth's surface are minimized by the lack of vertical mixing. On the other hand, a much deeper boundary layer exists in unstable conditions because of the more uniform lower atmospheric conditions that are present. Stable conditions most often occur overnight because there is no solar heating present to create a surface warm layer.

The Oak Creek and Transtower sites were both equipped with high-accuracy temperature sensors at two levels to study the effects of stability on the boundary layer wind conditions. Both locations experience stable conditions during the overnight hours and were unstable during the day. The hourly wind shear varies directly with respect to stability. Figure 5 contains plots of the diurnal temperature and wind shear profiles.

At Oak Creek, the environment is stable by a small margin (max ΔT ~ 0.4^{o}C) between 9 PM and 5 AM, while being unstable during the remainder of the day. The vertical ΔT range is between -1.8^{o}C and 0.4^{o}C. It should be noted that upper level temperature data were lost between 13 December 2004 and 5 April 2005. The mean hourly wind shear ranges between 0.17 and 0.32, with the highest values occurring during the most stable period.

The Transtower diurnal stability and wind shear changes are much greater in magnitude. The vertical ΔT ranges between -1.9^{o}C and 1.8^{o}C and the wind shear ranges between 0.11 and 0.47. Similar to Oak Creek, the peak wind shear values were observed during the most stable period.

2.5 Long-Term Wind Speed Estimate

The measure-correlate-predict method (MCP) of estimating long-term wind speeds correlates short-term data from a site with concurrent data from a long-term reference station. A regression or other relationship between the two stations is derived, and the long-term mean speed at the reference stations is applied to estimate the long-term speed at the site. When applying MCP, it is important to consider the distance between the two sites being correlated and select the appropriate sampling period (daily, hourly, etc.) which best corresponds to the meteorological relationship between those sites.[1]

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[1] Taylor, Mark, et al., "An Analysis of Wind Resource Uncertainty in Energy Production Estimates," Proceedings of the European Wind Energy Conference, November 2004.

Wind speed data from five National Weather Service (NWS) first-order monitoring stations were obtained for the period following the Automated Surface Observing System (ASOS) installation at each location. The data were subsequently analyzed to determine their suitability as long-term references.

The NWS upgraded the meteorological equipment at most of the country's weather stations beginning in the early- to mid-1990's. The upgrade included complete replacement of wind sensor models, the relocation of sensors to new 10 m towers (the old tower heights were 6 m) – often at different locations on airport grounds – and the use of automated data recording rather than the previous visual, dial-reading technique. This transition has often resulted in a discontinuity in NWS climatological data, in which the ASOS wind speeds are typically 5% to 10% lower than the pre-ASOS speeds. These discontinuities make it inappropriate to mix pre-ASOS and ASOS data records in MCP.

Table 32 contains a list of the five potential NWS reference stations, their ASOS commissioning dates, and their annual mean wind speeds.

Linear regression was used to correlate daily mean wind speeds from each monitoring site with two reference sites. Table 33 contains the results of each analysis. Each monitoring site long-term projection was computed using the reference station with the strongest relationship. In the case of Rosamond – where the two reference stations had identical r-squared values – a multiple linear regression was performed to determine if both sites are statistically significant. The regression equation is as follows:

Rosamond 109.7 m Wind Speed = 0.5921 * Lancaster 10 m Wind Speed + 0.6396 * Palmdale 10 m Wind Speed + 1.3080 m/s.

The r-squared value of the multiple regression improved to 0.81, which is a noticeable improvement over those from the individual single regressions (0.74). Since the regression coefficients with respect to both reference stations are statistically significant, the multiple regression was retained for the climatological adjustment.

The reference stations' annual mean wind speeds were examined to determine if any significant trends or discontinuities occurred over the period measured. Such patterns might indicate changing conditions around the stations, such as tree growth or clearing, as well as problems with equipment, which could introduce significant errors into the climatological adjustment. To limit that risk, stations showing significant trends or discontinuities are generally avoided unless the patterns can be confirmed by data from other stations. Figure 6 contains an annual mean wind speed plot of all the reference sites. Since the northern sites (Sacramento and Santa Rosa) and southern sites (Lancaster, Palmdale, and Vacaville) track each other well, respectively, they were all acceptable reference sites.

The reference station long-term mean wind speeds were substituted into the appropriate regression equation to yield the respective monitoring site long-term mean wind speeds. These projections were then extrapolated (or interpolated in some instances) to 70 m and 100 m heights using the site-specific wind shear coefficients. At sites where the mid-level sensor was closer to 70 m than the top-level, a long-term wind speed estimate was computed at that level and then used to project the 70 m speed. Table 34 summarizes the long-term wind speed projections.

2.6 Wind Speed Estimate Uncertainty

The uncertainties of the long-term wind speed projections are based on the instrument quality, level of correlation, and respective reference and monitoring site periods of record. As was the case with the four sites studied herein, it is ideal to have at least 12 months of data in order to fully observe the annual climate and significantly lessen the estimate uncertainty. The top monitoring height wind speed estimate uncertainties are as follows:

- Oak Creek: 4.7 %
- Rosamond: 4.1 %
- Transtower: 3.9 %
- Geyserville: 5.5 %.

There is an additional uncertainty measurement contained within long-term estimates computed using the mean wind shear exponent. Aside from the 100 m projection at Geyserville (60 m monitoring level), these uncertainties are small because the monitoring level is within 10 m of the projection level. Furthermore, most of the 70 m and 100 m projections are interpolations between known observations.

2.7 Tall Tower Campaign Summary

Wind data collected from four monitoring towers were analyzed and correlated with long-term reference sites to project the long-term wind speeds. Various wind characteristics were summarized and discussed; notably the vertical wind shear, which is most strongly affected by boundary layer stability. The respective site climatologies are heavily influenced by the sea breeze; a phenomenon that is induced by the large marine/continental temperature gradient. The onshore winds are channeled through gaps in the coastal mountains, causing sometimes strong prevailing winds that are concentrated into only a few direction sectors.

3.0 Sodar Campaign Results

3.1 Introduction

Sodar (<u>so</u>und <u>d</u>etection <u>a</u>nd <u>r</u>anging) is a useful addition to a meteorological monitoring program because it measures the wind profile up to and above the hub height of modern utility-scale wind turbines, which ranges from 65 m to 100 m, whereas meteorological towers are typically only 50 m to 60 m tall. By taking sodar measurements for a period of time near an existing met tower, the wind shear up to hub height can be characterized as a function of wind direction, wind speed, and time of day. By combining these wind shear values with long term met tower wind speed measurements, it is possible to calculate a more accurate annual-average wind speed at hub height than can be obtained from the met tower alone.

The sodar model used during this measurement campaign was an Atmospheric Research & Technology (ART) VT-1 permanently mounted in a trailer. This model is a state-of-the-art single frequency design that operates at an acoustic frequency of 4500 Hz. The sodar emits a series of acoustic pulses (“chirps”) by an array of small piezo-tweeters. The piezo-tweeters respond to echoes from the atmosphere generated by the small-scale temperature fluctuations associated with atmospheric turbulence. When the air is moving, the echoes are shifted in frequency due to the Doppler effect. By steering the acoustic beam using phase shifts among the speakers, and by analyzing the timing and the frequency shift of the returned echoes, the instrument derives the three components of wind velocity (the vertical and two horizontal components) at a range of heights from 30 m to 200 m above ground.

Sodar data was collected at seven sites, with at least one site in each of the five focus areas. Focus areas with multiple sodar sites are described in a single report, since a collective discussion of the results helps to better characterize the area.

3.2 Methodology and Data Quality

The sodar underwent a series of calibration and quality control checks prior to installation at each site. The calibration procedure uses ART’s *SodarTools* calibration software and other metering devices. These tests included: the sensitivity of the sodar to frequency shifts, antenna element output amplitude, the sodar pulse waveform output, amplifier gain and wave balance adjustments, and transponder testing. The sodar determines the wind speed from the Doppler shift in frequency; the sensitivity for this instrument is 0.14 m/s per 1 Hz frequency shift for horizontal wind components, and 0.04 m/s per 1 Hz for the vertical velocity component. The sodar can resolve a frequency shift of 1 Hz.

Sodar data were automatically e-mailed to AWS daily, along with the IP address of the computer, so that the sodar could be accessed remotely to examine signal quality and other parameters. Time synchronization between the sodar computer and the datalogger was checked by examination of the wind direction time series. In addition to the above, the following data quality checks on the data were performed:

1. Periods of precipitation, indicated by an onsite rain gauge logged with the sodar data, were removed from the data set. Further data filtering was done to obtain samples with adequate signal amplitude and signal-to-noise ratio.

2. Signal amplitude profiles were examined for fixed-echo effects.

3. The sodar speeds were converted to a scalar equivalent for comparison with anemometer data. The reason for this conversion is that the sodar unit measures the vector average of the horizontal components of the wind in each data sample. The vector average is generally less than the average scalar speed because wind components that are transverse to the mean direction tend to cancel each other. The conversion to scalar equivalent was done using a factor calculated from the standard deviation of the sodar vertical velocity, which is a surrogate for the standard deviation of the wind direction.

4. Adjustments were made for variations in the sodar beam geometry. The sodar determines the horizontal components of the wind speed from the radial velocities along two orthogonal beams tilted (nominally) at 18^o from the vertical. The actual tilt angle is affected by the effective array spacing, and the speed of sound, which in turn is affected by the temperature. For the sodar used here specifically, an array spacing of 8.9 cm was used, while the temperature adjustment was based on the reference tower temperature.

5. For the purpose of making a valid comparison between sodar and tower, an adjustment to the tower wind speeds based on the sodar vertical turbulence intensity was made to account for overspeeding by the anemometers. This adjustment was about 2.3% overall for Antelope Valley and 3.8% for Oak Creek.

3.3 Antelope Valley and Oak Creek Sodar Campaigns

3.3.1 Summary

Sodar studies during the summer of 2004 at two sites in Southern California, one in Antelope Valley and the other at an Oak Creek Energy Systems wind farm near Tehachapi, have determined shear parameters and other wind characteristics from 30 m to 200 m height above the ground. Both sites have diurnal patterns in the wind speed and direction consistent with thermal circulations. The Antelope Valley site had an average shear exponent of 0.08 above 50 m, and wind speeds 14% higher than the concurrent measurements at the Rosamond Tower. The Oak Creek site, with complex terrain and scrub vegetation, had shear exponents of 0.23 to 0.25 above 50 m.

3.3.2 Site Descriptions

Sodar measurements were made at two locations in southern California. The locations and periods of measurement at each site are given in Table 1.

Table 1: Locations and dates of the Oak Creek and Antelope Valley sodar studies. Also shown are the locations of the two tall towers used for reference.

Name	Latitude	Longitude	Elevation	Start	End
Oak Creek	35.03183	-118.3458	1291	6/22/2004	7/2/2004
Antelope Valley	34.71608	-118.3591	795	7/2/2004	7/26/2004
Rosamond Tower	34.85083	118.1569	703	7/2/2004	7/2/2005
Oak Creek Tower	35.03139	118.3469	1301	4/26/2004	6/30/2005

Data from the Rosamond tower will be used as reference measurements for the Antelope Valley site, while the Oak Creek tower will be used for the Oak Creek sodar study. The tower instrumentation is described in Table 35 in the Appendix.

3.3.3 Antelope Valley Site Description

The Antelope Valley site is a relatively flat, cultivated field with very low vegetation or bare soil (Figure 7 and Figure 8). The terrain slopes very gradually down from east to west. There were no obstructions for more than a kilometer in all directions. A transmission line runs through the area to the east of the sodar location. There was also a 21 m tower fitted with a cup anemometer and vane at the Antelope Valley site, which was located about 150 m to the E of the sodar location.

3.3.4 Oak Creek Site Description

This Oak Creek site is in an existing wind plant (Figure 9 to Figure 11). The terrain is quite complex, and there are numerous wind turbines and meteorological towers in the area.

3.3.5 Results

The two sodar measurement sites exhibited different average flow regimes, though there are some characteristics in common. The predominant flow at both Antelope Valley and Rosamond Tower was from the SW (Figure 12), with a clockwise turn in the late afternoon and after sunset that may be due to inertial oscillation(Figure 13). Directions generally agree between the Rosamond tower and the Antelope Valley site, even though they are separated by 20 km or more. Wind speed increased during the day from its minimum at around 0800 h, reaching a maximum around 1700 h.

The average flow at Oak Creek was westerly in the afternoon, building in speed from 1400 h to 1700 h (Figure 14). In the early evening, the flow turned sharply NW and a clockwise inertial turning of the wind began, continuing until 2300 h. Maximum speeds occurred from midnight to 3 AM on these NW winds.

The sodar measurement periods for both Antelope Valley and Oak Creek appear to be representative of the 2004 summer conditions, i.e. no large change occurred in the flow regime between the Oak Creek and Antelope Valley measurement periods.

More detailed results are presented in separate sections for each site, below and in the Appendices.

3.3.5.1 Antelope Valley Results

At the Antelope Valley site, the overall availability of the sodar was 100%. Of the 2725 wind profiles analyzed after additional filtering for adequate signal-to-noise ratio, 2337 were qualified samples on the basis of having 50 m wind speeds $\geq$ 5 m/s. Table 2 presents a summary of wind speed and wind shear statistics over the measurement period, for concurrent sodar and tower observations. The statistics in the table are given for all wind speeds and for speeds $\geq$ 5 m/s at 50 m, which is the relevant speed range for wind turbines. Tower and sodar shear parameters are calculated for the 70 m to 90 m (for sodar) or 77 m to 110 m (for tower) interval and the measured sodar shear parameter is given for the 50 m to 80 m layer.

Table 2: Mean statistics for coincident data from the Antelope Valley sodar and Rosamond tower, for 50 m sodar speeds $\geq$ 5 m/s.
Tower speeds at 120 m are extrapolated using the tower 77/45 m shear parameter.

Parameter	**Sodar**			**Tower**		
Mean Speed (m/s)	Height, m	All U	U $\geq$ 5 m/s	Height	All U	U $\geq$ 5 m/s
	50	8.6	9.4	45	6.6	7.1
	80	8.8	9.7	77	7.3	7.8
	110	9.0	9.8	110	8.0	8.6
	120	9.0	9.9	120	*8.2*	*8.7*
Shear parameter	90/70	0.05	0.05	110/77	0.23	0.22
	80/50	0.08	0.08	110/45	0.27	0.27
Number of Profiles @ 110 m		2725	2337		2725	2337

Table 3 differentiates shear exponents by wind direction sector for winds $\geq$ 5 m/s, while Table 4 does the same for even windier cases of speeds $\geq$ 8 m/s at 50 m. Mean shear values for the tower (110/77 m and 110/45 m) and sodar (90/70 m and 80/50 m) are given. The upper profile sodar shear is calculated only to 90 m because in one direction sector the sodar altitude performance was limited to that height. The mean speed difference between the sodar and tower systems as a function of wind direction at 50 m, 80 m, 110 m and 120 m are also given in Table 3 and Table 4, where the tower data were extrapolated to 120 m using the 77/45 m tower shear exponent.

The wind roses for the sodar and tower during the Antelope Valley sodar study period are similar(Figure 15), having the strongest winds from the SW.

Sodar mean speeds and shear parameters by hour of day and by speed are presented in Figure 16 and Table 36, respectively, in the Appendix.

Table 3: Profile statistics by wind direction for the Antelope Valley sodar and Rosamond tower, for 50 m sodar speeds ≥5 m/s

Direction	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW
Tower shear (110/77 m)					0.14	0.37	0.28	
Tower shear (110/45 m)					0.18	0.42	0.28	
Sodar shear (90/70 m)					0.00	0.10	0.14	
Sodar shear (80/50 m)					0.04	0.13	0.12	
Mean Sodar U @50 m-Tower U @ 45 m					1.8	3.1	2.2	
Mean Sodar U @80 m-Tower U @ 77m					1.5	2.4	1.7	
Mean Sodar U @90 -Tower U @ 110 m					0.8	1.6	1.3	
Mean Sodar U -Tower U @ 120 m					NA	1.6	1.2	
Number of Profiles					1218	1001	118	

Table 4: Profile statistics by wind direction for the Antelope Valley sodar site and Rosamond tower, for 50 m sodar speeds ≥8 m/s

Direction	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW
Tower shear (110/77 m)					0.14	0.36	0.40	
Tower shear (110/45 m)					0.18	0.40	0.42	
Sodar shear (90/70 m)					0.01	0.05	0.16	
Sodar shear (80/50 m)					0.04	0.10	0.14	
Mean Sodar U @50 m-Tower U @ 45 m					1.9	3.8	4.7	
Mean Sodar U @80 m-Tower U @ 77m					1.5	3.1	3.9	
Mean Sodar U @90 -Tower U @ 110 m					0.9	2.1	3.3	
Mean Sodar-Tower U @ 120 m					NA	1.9	3.3	
Number of Profiles					1026	533	35	

Although the wind directions agreed fairly well between the Antelope Valley and Rosamond tower sites, the mean wind speeds at Antelope Valley were substantially higher, on the average (Figure 17 through Figure 21). The regression of hourly-averaged sodar 80 m wind speeds on tower 77 m speeds yields a slope of 0.6667, but an intercept of 3.71 m/s, with an R^2 of 0.48. Forced through the origin, the slope of the regression line is 1.07. The mean speeds are 13 to 14% higher at the sodar site than at the Rosamond tower.

The shear parameters from the sodar profiles are very low overall, as would be expected given the low cover, homogeneous fetch, and simple terrain surrounding the site. The tower and the sodar shears vary by wind direction; in particular, shears are higher for the WNW wind direction. This is because that sector is represented only by nighttime hours, when thermally stable conditions occur, and the flow is decoupled from surface friction to a greater degree. Near-zero or slightly negative shears were measured above 80 m at mid-day.

The vertical velocity rose (Figure 22) is consistent with of the slope at the site. Because of the generally high wind speeds, the flow inclinations were small in magnitude, and they were uniform with height.

Comparison of the 21 m speeds on the mast near the sodar location with the sodar speeds is given in Table 5 and Figure 23. The sodar 80 m speeds were 1.023 times greater than the 21 m speeds, and the 30 m sodar speeds were actually less than the mast speeds at 21 m. The mean annual speed for the 21 m anemometer for years 2001 through 2004 was 6.3 m/s. Using the proportion found in this study, this would produce a long-term annual estimated 80 m speed of 6.48 m/s. If on the other hand the long-term mast speed is sheared up to 80 m using the 80/50 m shear parameter of 0.08 (Table 2), the long-term 80 m speed would be 7.1 m/s. The wind map 30 m annual speed at the sodar location is 7.4 m/s. The results from the 21 m mast should be viewed with caution because the mast anemometer was top-mounted on a stub and therefore may overestimate the wind speed due to acceleration of wind flow at the mast top.

Table 5: Antelope Valley sodar wind speeds compared to the 21 m speeds from the Munz Ranch mast.
Data obtained from Oak Creek Energy Systems.

	All Speeds	**U>5 m/s**
Tower 21 m Speed	8.5	9.5
Sodar 30 m speed	7.9	8.8
Sodar 80 m speed	8.7	9.7
Number of Profiles	2902	2462

3.3.5.2 Oak Creek

At the Oak Creek site the overall sodar availability was 92%. Of the 990 wind profiles analyzed after additional filtering for adequate signal-to-noise ratio, 744 were qualified samples on the basis of having 50 m wind speeds $\geq$ 5 m/s.

Table 6 presents a summary of wind speed and wind shear statistics over the measurement period, for concurrent sodar and tower observations. The statistics in the table are given for all wind speeds and for speeds $\geq$ 5 m/s at 50 m, which is the relevant speed range for wind turbines.

Table 6: Mean statistics for coincident data from the Oak Creek sodar and tower. "U" indicates 50 m sodar speed. Tower speeds at 110 m are extrapolated using the tower 70/53 m shear parameter.

Parameter	Sodar			Tower		
Mean Speed (m/s)	Height, m	All U	U $\geq$ 5 m/s	Height	All U	U $\geq$ 5 m/s
	50	7.9	9.3	53	8.6	10.0
	70	8.5	10.0	70	9.0	10.6
	90	9.0	10.6	88	9.5	11.2
	110	9.2	10.9	110	10.0	11.9
Shear parameter	90/70	0.21	0.22	88/70	0.23	0.22
	80/50	0.23	0.23	88/53	0.21	0.21
Number of Profiles @ 110 m		990	744		990	744

At the Oak Creek site there was a period of sustained, very high NW winds from day 177 to 179 (June 25 to 27). This period did not exhibit the same diurnal oscillation in wind direction and speed, as the rest of the Oak Creek measurement period did. During this anomalous period the sodar wind speeds were considerably lower than the reference tower measurements, possibly because the sodar data were bandwidth-limited. This can result when high wind speeds occur that are aligned with one axis of the sodar; extreme values of the wind can then be truncated by the bandwidth setting. The altitude performance of the instrument was also much reduced during this period. The remainder of the analyses presented for this site pertain to the sodar study period excluding the anomalous period. Table 7 gives the mean statistics for the more restricted data set.

Table 7: Mean statistics for coincident data from the Oak Creek sodar and tower, excluding the high wind event of days 177-179.
Tower speeds at 110 m are extrapolated using the tower 70/53 m shear parameter.

Parameter	**Sodar**			**Tower**		
Mean Speed (m/s)	**Height, m**	**All U**	**U $\geq$ 5 m/s**	**Height**	**All U**	**U $\geq$ 5 m/s**
	50	6.7	8.1	53.0	6.9	8.3
	70	7.2	8.7	70.0	7.3	8.9
	90	7.6	9.3	88.0	7.8	9.5
	110	8.0	9.8	110.0	8.2	10.1
Shear parameter	90/70	0.25	0.27	88/70	0.29	0.29
	80/50	0.23	0.25	88/53	0.25	0.26
Number of Profiles		783	537		783	537

Table 8 and Table 9 give the mean shear parameters for tower and sodar as well as mean speed differences by direction sector for observations with 50 m speeds $\geq$ 5 m/s and $\geq$ 8 m/s, respectively.

Table 8: Profile statistics by wind direction sector for the Oak Creek site, with 50 m sodar speeds >5 m/s

Direction	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW
Tower shear (88/70 m)				0.42	0.39	0.27	0.30	0.20
Tower shear (88/53 m)				0.25	0.23	0.26	0.28	0.19
Sodar shear (90/70 m)				0.09	0.08	0.04	0.31	0.27
Sodar shear (80/50 m)				0.09	0.09	0.07	0.28	0.32
Mean Sodar U @50 m- Tower U @ 53 m				0.3	0.5	-0.6	-0.3	-0.4
Mean Sodar U @70 m- Tower U @ 70m				0.2	0.6	-1.0	-0.1	0.1
Mean Sodar U @90 - Tower U@ 88 m				-0.1	0.1	-1.6	-0.1	0.3
Mean Sodar U -Tower U @ 110 m				0.1	0.2	-2.2	-0.4	-0.1
Number of Profiles				10	47	51	337	90

Table 9: Profile statistics by wind direction sector for the Oak Creek site, for 50 m sodar speeds >8 m/s

Direction	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW
Tower shear (88/70 m)						0.24	0.29	0.26
Tower shear (88/53 m)						0.25	0.28	0.27
Sodar shear (90/70 m)						0.01	0.25	0.26
Sodar shear (80/50 m)						0.04	0.25	0.31
Mean Sodar @50 m- Tower U @ 53 m						0.1	0.3	-0.8
Mean Sodar @70 m- Tower U @ 70m						-0.5	0.5	-0.6
Mean Sodar @90 - Tower U@ 88 m						-1.2	0.4	-0.5
Mean Sodar-Tower U @ 110 m						NA	-0.2	-2.0
Number of Profiles						23	102	15

The wind roses for the sodar and tower during the Oak Creek sodar study period are similar (Figure 24), having the strongest winds from the NW.

Sodar mean speeds and shears by hour of day and by speed are presented in Figure 25 and Table 37, respectively, of the Appendix.

The regression of hourly-averaged 70 m sodar winds on the 70 m tower wind speeds yields a slope of 0.87 and a significant intercept of 1.05 m/s, with an R^2 of 0.80. Though the tower was only about 100 m from the sodar, the local terrain is quite complex, and it is likely that some sodar measurements, particularly those from the SSW but perhaps also those from the NW, may be influenced by turbine wakes. Comparisons of the sodar and tower speeds are shown in Figure 26 through Figure 30.

The diurnal oscillation in wind speed and direction at Oak Creek is most likely related to a mountain-valley circulation generated by the Tehachapi Mountains.

The vertical velocity rose at 50 m (Figure 31) indicates that the flow is following the local terrain near the sodar, but the vertical profiles of the flow inclination (Figure 32) suggest that at higher heights, the terrain further upwind is influential. Wind from the SSW has very high vertical turbulence intensity throughout the profile, and may be influenced by wakes from the turbines in that direction. Similarly, vertical turbulence intensity (sigma-W/U) increases from 30 m to 50 m in the WNW and NNW wind direction sectors, probably as a result of the complex terrain but also possibly because of turbine wakes.

The regular shift in wind direction in the late afternoon (Figure 33) appears to occur at all heights (below 150 m) simultaneously (within one averaging period), i.e. there is no significant wind direction shear for any significant length of time.

3.3.6 Conclusions

The sodar studies from Antelope Valley and Oak Creek provide a wide range of information for the lower 200 m of the atmospheric boundary layer in an area with complex mesoscale meteorology. From these studies we draw the following preliminary conclusions:

- The Antelope Valley and Oak Creek sodar study periods appear to be representative of their respective locales, as well as representative of the conditions during the summer of 2004.
- Both sites have regular diurnal cycles of wind direction and speed, punctuated by periods of high wind speed and more constant wind direction.
- The Antelope Valley site had wind speeds that were 14% higher than the Rosamond tower speeds during the measurement period.
- Both local and regional terrain effects, as well as turbine wake effects, are at work in the Oak Creek data set. The regional terrain controls the diurnal cycle of wind speed and direction, while the local effects are apparent in the shear, flow inclination and turbulence intensity profiles. Further sodar studies at existing wind farms in southern California could provide useful information on wake effects.

3.4 Mayacamas Mountains Sodar Campaign

3.4.1 Summary

Sodar studies during the summer of 2004 at two sites in the Mayacamas Mountains have determined shear parameters and other wind characteristics from 30 m to 200 m height above the ground. Both sites, located in steep terrain, have diurnal patterns in the wind speed and direction consistent with thermal circulations; the strongest winds at each site were associated with drainage winds. The dominance of these local circulations was enhanced by the low wind speeds in the region overall during the sodar study period. The Mayacamas site had shear of 0.21 from 60 m to 80 m, while the lower profile shear was 0.08. The second site (Calpine), located on a ridge top, had 60 m to 80 m shear of 0.08 for the limited number of qualified samples. Both sites had lower wind speeds overall than the Geyserville tower.

3.4.2 Site Descriptions

Sodar measurements were made at two locations in southern California. The locations and periods of measurement at each site are given in Table 10.

Table 10: Locations and dates of the Mayacamas and Calpine sodar studies. Also shown are the locations of the three towers used for reference in this report.

Name	Latitude	Longitude	Elevation	Start	End
Mayacamas Sodar	38.75880	-122.75390	951m	6/8/2004	6/29/2004
Calpine Sodar	38.76480	-122.76590	999m	6/29/2004	7/22/2004
Geyserville Tower	38.762194	-122.84111	977m	7/28/2004	6/30/2005
Calpine Unit 13	38.599444	-122.726111	1006m	1/1/2004	Unknown
Calpine Unit 17	38.841944	-122.79611	927m	1/1/2004	Unknown

Data from the Geyserville tower (Figure 34), located 7 km NW of the sodar sites, will be used as reference measurements for both sodar locations. The Geyserville tower instrumentation is described in Table 38 in the Appendix. Additional comparisons will be made to the Calpine Meteorological Station #17 site. Comparisons to a second Calpine meteorological station, Unit 13, were done, but under the relatively low wind speed conditions for this study, this station was too far from the sodar locations to yield meaningful results.

The Mayacamas Mountains comprise a complex system of steep-sided ridges (Figure 35). The two sodar sites and the Geyserville tower site are all in areas of steep terrain with rough cover (Figure 36 through Figure 40).

3.4.2.1 Mayacamas Site Description

The Mayacamas site is a steep hillside with shrubby vegetation and low conifers up to 2 m tall (Figure 36 and Figure 37).

3.4.2.2 Calpine Site Description

The sodar was moved on June 29 to a ridge top 1.2 km from the original site (Figure 38 to Figure 40). Vegetation at this site was a dry scrub forest.

3.4.3 Results

There were generally low wind speeds throughout the period that the sodar was located in the Mayacamas Mountains. Thermally-driven local circulations (mountain-valley circulations) dominated the entire period. The two sodar measurement sites exhibited different average flow regimes, which are illustrated by the hodographs in Figure 41 and Figure 42. The Geyserville tower hodograph is similar to that for the Mayacamas site, rather than the Calpine site. Directions generally agreed between the Mayacamas sodar site and the Geyserville tower site, even though they are separated by 7.6 km. The agreement between the Calpine sodar site and Geyserville tower wind directions was less good.

More detailed results are presented in separate sections for each site, below and in the Appendices.

3.4.3.1 Mayacamas

At the Mayacamas site, the overall availability of the sodar was 100%. Of the 2840 wind profiles analyzed after additional filtering, 885 were qualified samples on the basis of having 50 m wind speeds $\geq$ 5 m/s. Table 11 presents a summary of wind speed and wind shear statistics over the measurement period, for concurrent sodar and Geyserville tower observations. The statistics in the table are given for all wind speeds and for speeds $\geq$ 5 m/s at 50 m, which is the relevant speed range for wind turbines. Tower and sodar shear parameters are calculated for the 40 m to 60 m (for sodar) or 44 m to 60 m (for tower) interval and the measured sodar shear parameter is given for the 60 m to 80 m layer.

Table 11: Mean statistics for coincident data from the Mayacamas sodar and Geyserville tower, for 50 m sodar speeds $\geq$ 5 m/s.
Tower speeds at 80 m and 110 m are extrapolated using the tower 60/44 m shear parameter.

		Sodar			Tower	
Parameter	**Height, m**	**All Speeds**	**U$\geq$ 5 m/s**	**Height, m**	**All Speeds**	**U$\geq$ 5 m/s**
Speed, m/s	30	4.2	7.4	29	5.6	9.2
	40	4.2	7.5	44	5.8	9.0
	60	4.3	7.7	60	5.6	8.8
	80	4.7	8.2	80	5.7	9.4
	110	5.2	8.7	110	5.7	9.6
Shear	60/40	0.06	0.08	60/29	0.01	0.06
	80/60	0.31	0.21	60/44	-0.06	0.07
Number of Profiles		2840	855		2840	855

Table 12 differentiates shear exponents by wind direction sector for winds $\geq$ 5 m/s, while Table 13 does the same for even windier cases of speeds $\geq$ 8 m/s at 50 m. Mean shear values for the tower and sodar are given. The mean speed difference between the sodar and tower systems as a function of wind direction at 60 m, 80 m and 110 m are also given in

Table 12 and while Table 13, where the tower data were extrapolated using the 60/44 m tower shear exponent.

Table 12: Profile statistics by wind direction sector at the Mayacamas sodar site, for 50 m sodar speeds ≥5 m/s

Direction	N	NE	E	SE	S	SW	W	NW
Tower shear (60/29 m)	0.10	0.03	-0.11		-0.06	-0.02	0.23	0.06
Tower shear (60/44 m)	0.12	0.04	-0.41		-0.05	-0.02	0.23	0.08
Sodar shear (60/40 m)	0.14	0.07	-0.21		-0.18	-0.13	0.21	0.09
Sodar shear (80/60 m)	0.24	0.13	0.04		-0.08	-0.02	0.28	0.25
Tower U – Sodar U @ 60 m	-2.9	0.7	-2.1		-0.6	-0.1	-1.3	-2.1
Tower U – Sodar U @ 80 m	-2.8	0.8	-1.6		-0.6	-0.1	-1.5	-1.8
Tower U – Sodar U @ 110 m	-2.4	1.3	-0.6		N/A	0.1	-1.3	-1.4
Number of Profiles	171	135	5		11	85	10	438

Table 13: Profile statistics by wind direction sector at the Mayacamas sodar site, for 50 m sodar speeds ≥8 m/s

Direction	N	NE	E	SE	S	SW	W	NW
Tower shear (60/29 m)	0.10	0.02						0.07
Tower shear (60/44 m)	0.14	0.03						0.09
Sodar shear (60/40 m)	0.17	0.00						0.12
Sodar shear (80/60 m)	0.22	-0.01						0.14
Tower U – Sodar U @ 60 m	-2.6	3.1						-1.8
Tower U – Sodar U @ 80 m	-2.6	3.2						-1.7
Tower U – Sodar U @110 m	-2.1	3.2						-1.7
Number of Profiles	71	29						167

The wind roses (Figure 43) for the sodar and tower during the Mayacamas sodar study period are similar, having the strongest winds from the NNW; these are associated with the downslope flow that became established after sunset through the very early morning.

The wind speeds at the Mayacamas sodar site were generally lower than those at the Geyserville tower site (Figure 44 and Figure 45). The regression of hourly-averaged sodar 60 m wind speeds on tower 60 m speeds yielded slopes of 0.70 and 0.77 for regressions forced through the origin, for all wind speeds and for speeds $\geq$ 5 m/s respectively. The sodar 60 m speeds were 1.3 and 1.1 m/s slower for all wind speeds and for speeds $\geq$ 5 m/s, respectively.

The steep terrain around both the tower and sodar sites leads to very low, sometimes even negative, shear. The tower and the sodar shears vary by wind direction; in particular, shears were higher for the W wind direction, but the number of observations is very low for this direction sector. It is possible that the higher values result from the fact that those observations occurred at night during stable conditions. Variations in sodar speeds and shear by hour of day are seen in Figure 46. The average profiles for those sectors with sufficient qualifying observations are shown in Figure 47 to Figure 51**.**

The vertical velocity rose Figure 52 is consistent with of the slope at the site, with relatively large vertical components of the flow from every direction.

The hourly-averaged wind speeds at the Calpine Unit 17 meteorological station were compared to those from the sodar (Figure 53). Relatively poor correlation was observed overall. The slope of the regression of sodar 80 m speeds on the meteorological station 10 m speeds, forced through a zero intercept, was 1.13. However, given the low wind speeds overall, and the poor correlation between the two, this result should be viewed with caution.

3.4.3.2 Calpine

At the Calpine site the overall sodar availability was 73%. Of the 1183 wind profiles analyzed after additional filtering, 79 were qualified samples on the basis of having 50 m wind speeds $\geq$ 5 m/s. Table 14 presents a summary of wind speed and wind shear statistics over the measurement period, for concurrent sodar and 60 m tower observations. The statistics in the table are given for all wind speeds and for speeds $\geq$ 5 m/s at 50 m, which is the relevant speed range for wind turbines.

Table 14: Mean statistics for coincident data from the Calpine sodar site and Geyserville tower, for all speeds and 50 m sodar speeds $\geq$ 5 m/s.
Tower speeds at 80 m and 110 m are extrapolated using the tower 60/44 m shear parameter.

Sodar	Tower

Parameter	Height, m	All Speeds	U≥5 m/s	Height, m	All Speeds	U≥5 m/s
Speed	30	2.7	6.2	29	3.9	4.2
	40	2.7	6.3	40	4.1	4.3
	60	2.7	6.5	60	4.0	4.2
	80	3.0	6.7	80	3.8	4.2
	110	3.8	7.2	110	3.8	4.2
Shear	60/40	0.00	0.07	60/29	-0.05	0.00
	80/60	0.35	0.09	60/44	-0.16	-0.07
Number of Profiles		1183	79	N	1183	79

Table 15 gives the mean shear parameters for tower and sodar as well as mean speed differences by direction sector for observations with 50 m speeds $\geq$ 5 m/s There were insufficient data with winds at 50 m $\geq$ 8 m/s, so no table of shears under this category is presented.

Table 15: Profile statistics by direction for the Calpine sodar site and Geyserville tower, for 50 m sodar speeds ≥5 m/s

Direction	N	NE	E	SE	S	SW	W	NW
Tower shear (60/29 m)	-0.03	0.01	0.05		-0.05			-0.05
Tower shear (60/44 m)	-0.07	-0.06	-0.06		-0.09			-0.06
Sodar shear (60/40 m)	0.12	0.07	0.06		-0.09			0.16
Sodar shear (80/60 m)	0.36	0.05	0.05		-0.02			0.19
Tower U – Sodar U @ 60 m	1.5	2.5	3.9		-0.3			0.2
Tower U – Sodar U @ 80 m	1.3	2.5	3.8		-0.3			0.2
Tower U – Sodar U @110 m	3.7	2.8	4.1		-0.1			2.4
Number of Profiles	11	22	30		8			6

The wind roses for the sodar and tower during the Calpine sodar study period highlight the differing manifestations of the thermally-driven circulation at each site (Figure 54). The strongest winds at the Calpine site occurred in the early morning hours when the wind shifted to the ENE (indicated in the hodograph, Figure 42).

The regression of hourly-averaged 60 m sodar winds on the 60 m tower wind speeds yields a slope of 0.58, forced through zero(Figure 55). There was a poor correlation of the winds at this site with the tower, emphasizing again the difference in wind regimes between the two, even though this site was only about 1.2 km from the Mayacamas sodar site.

The shears again are quite low, often negative, at this site (Figure 56 through Figure 59), which is consistent with the influence of the steep terrain. The low wind speeds overall resulted in few qualified observations, so that the shears by direction (

Table 15), shear by hour of day (Figure 60) and shear by wind speed (Table 40) should be viewed with caution.

The vertical velocity rose at 50 m (Figure 61) indicates that the flow is following the local terrain near the sodar. Again there is a poor correlation (Figure 62) between the 80 m hourly speeds at this site and the 10 m speeds at the Calpine Unit 17 meteorological station, which is 9 km to the NW.

3.4.4 Conclusions

Due to the dominance of thermally-driven circulations, and the complex terrain in the area, the diurnal oscillation in wind direction different at different locations in the ridge, so wind directions often don't agree. Calpine Unit 17 directions agreed more closely than Unit 13.

The sodar studies conducted in the Mayacamas Mountains have provided insight into the thermally-driven circulations in this complex area, although the low wind speeds experienced generally limit the usefulness of these data for long-term speed estimates. From these studies we draw the following preliminary conclusions:

- The steep terrain in the region lead to very low shears for the period of record, despite the presence of significant surface roughness. Shear parameters are sometimes slightly negative.
- Under the low wind speed conditions in this study period, local circulations dominate, so that winds at locations separated by only a few km are often not coupled to one another.
- The strongest wind speeds in these conditions tend to occur on downslope (drainage) winds while the surface is cooler than the air above it

Given the dominance of the local circulations in this study period, it is not unexpected that the sodar wind speeds and those from the surface meteorological stations 10 km to 20 km from the sodar sites are not well-correlated. Future sodar studies in the Mayacamas Mountains could yield very useful information if a period with high wind speeds is targeted.

In these data sets, no correction for either flow inclination or turbulence intensity using the sodar data was applied to the anemometers, since these factors are likely to be quite different between tower and sodar locations. These factors might account for differences of about 3-5% between sodar and tower.

3.5 Mojave Sodar Campaign

3.5.1 Summary

A sodar study during the summer of 2004 at a site in the Mojave desert has determined shear parameters and other wind characteristics from 30 m to 200 m height above the ground. The site was located in a broad valley between two mountain ranges. The energy-containing winds were dominated by winds from the SW and W, which represent drainage flows down the east-facing slope of this site. Such winds occurred regularly each evening after 1700 LST and persisted until 0200 or 0300 the next morning, with mean speeds of 12.1 m/s at 80 m. The overall 80/50 m wind shear was **0.10** for the study period. Wind shear for the important sectors was constant with height.

3.5.2 Site Description

Sodar measurements were made in the Mojave Desert in southern California. The location and period of measurement are given in Table 16.

Table 16: Location and dates of the Mojave sodar study

Name	Latitude	Longitude	Elevation	Start	End
Mojave	35.09097	116.90022	804m	8/6/2004	9/9/2004

The Mojave site is rocky and sandy with sparsely scattered low shrubs. (Figure 63 and Figure 64). There is a significant slope from the west to east (lower terrain to the E).

3.5.3 Results

At the Mojave site, the overall availability of the sodar was 60%. All of the data loss was due to a high-temperature shutdown of a power system component which occurred near noon each day until August 19, when the component was bypassed. After that point, the availability was 90%. Of the 2515 wind profiles analyzed after additional filtering, 1179 were qualified samples on the basis of having 50 m wind speeds $\geq$ 5 m/s.

Table 17 presents a summary of wind speed and wind shear statistics by wind direction over the measurement period.

Table 17: Mean statistics for the Mojave sodar study by wind direction sector

Direction	All	N	NE	E	SE	S	SW	W	NW
U@30 m	5.7	2.8	2.2	2.0	2.1	2.9	6.8	9.7	2.2
U@50 m	6.0	2.6	2.2	2.1	2.1	3.1	7.0	10.1	1.9
U@80 m	6.4	2.7	2.5	2.5	2.7	3.4	7.3	10.7	1.9
U@110 m	7.0	3.1	2.7	2.9	3.5	3.7	7.5	11.4	2.4
U@120 m	7.1	3.3	2.8	2.8	3.5	3.8	7.5	11.6	2.5
U@140 m	7.2	3.4	3.1	2.6	3.1	3.9	7.5	12.0	3.6
Shear (50/30 m)	0.08	-0.09	0.00	0.09	-0.02	0.11	0.06	0.09	-0.23
Shear (80/50 m)	0.16	0.03	0.26	0.39	0.55	0.22	0.10	0.11	-0.02
Shear (110/80 m)	0.26	0.50	0.34	0.39	0.84	0.27	0.09	0.20	0.68
Number of Profiles	2515	62	145	500	275	105	328	1034	66

Table 18 and

Table 19 do the same for even windier cases of speeds ≥5m/s and ≥ 8 m/s at 50 m respectively. Mean wind speeds at selected heights and shear values for 3 layers are given.

Table 18: Mean statistics for the Mojave sodar study, for 50 m sodar speeds ≥ 5 m/s, by wind direction sector.
Sectors with fewer than 10 observations are omitted.

Direction	All	E	SE	S	SW	W
U@30 m	10.0	5.7	5.9	4.9	8.5	10.9
U@50 m	10.6	5.9	6.3	5.8	8.8	11.5
U@80 m	11.1	6.4	7.2	6.4	9.2	12.1
U@110 m	11.6	7.0	9.1	6.3	9.2	12.6
U@120 m	11.8	7.0	9.6	6.4	9.2	12.8
U@140 m	12.0	6.6	9.7	6.5	9.2	13.2
Shear (50/30 m)	0.10	0.07	0.13	0.32	0.08	0.09
Shear (80/50 m)	0.10	0.17	0.28	0.19	0.08	0.11
Shear (110/80 m)	0.13	0.28	0.74	-0.02	0.02	0.14
Number of Profiles	1179	16	30	19	233	875

Table 19: Mean statistics for the Mojave sodar study by direction, for 50 m sodar speeds ≥ 8 m/s.
Sectors with fewer than 10 observations are omitted.

Direction	All	SW	W
U@30 m	11.4	10.2	11.7
U@50 m	12.0	10.6	12.3
U@80 m	12.6	11.0	12.9
U@110 m	13.0	11.1	13.4
U@120 m	13.2	11.1	13.6
U@140 m	13.5	11.4	13.9
Shear (50/30 m)	0.10	0.07	0.09
Shear (80/50 m)	0.11	0.07	0.11
Shear (110/80 m)	0.10	0.02	0.11
Number of Profiles	892	138	752

The SW and W wind direction sectors were the most important for energy (Figure 65), but light E and SE winds occupied 31% of the data record (Table 17). The strong downslope SW and W winds only occurred from shortly after sunset until about 0200, and then slackened abruptly on most nights. Shear and speed profiles are shown by time of day and wind speed, in Figure 66 and Table 41 respectively. The hodograph (Figure 67) illustrates the average diurnal cycle in the wind speed and direction, which results from a thermal circulation established by the sloping terrain. The easterly aspect of the slope causes a relatively early “meteorological sunset” as the sun is no longer shining directly on the slope after about 1700 LST. The cooling of the surface initiates a drainage flow that lasts for about 8 hours.

The downslope flow exacerbated the effect of the dry atmospheric conditions found in the Mojave on sound propagation, so that at times, the altitude performance of the instrument was limited to 100 m; this was especially true from 1800 to 1900, when there was little in the way of turbulent temperature fluctuations to produce backscattered acoustic signal.

The shears were low overall (~0.10 to 0.12) and fairly constant with height (Figure 68 through Figure 71). The overall shear parameter for observations with 50 m speeds > 5 m/s was **0.10** (Table 18); higher shear parameters were observed for the SE sector, but these formed a very small percentage of the qualified samples.

The vertical velocity rose (Figure 72) is consistent with the slope at the site, with relatively large vertical components of the flow from the E and W. Flow inclination was -0.06 to -0.07 on the downslope SW and W winds.

3.5.4 Conclusions

The Mojave sodar study has determined shear parameters for the SW and W wind direction sectors which represented nearly all of the energy-producing winds for the study period. These sectors contain drainage flow which is established around sunset and continues until 0200 or 0300. The overall 80/50 m shear parameter for this site was **0.10**. The shear remained fairly constant with height

3.6 San Gorgonio Sodar Campaign

3.6.1 Summary

Sodar studies during the summer of 2004 at a site in the San Gorgonio Pass have determined shear parameters and other wind characteristics from 30 to 200 m height above the ground. The site was located in a broad valley between two mountain ranges. Westerly winds at speeds greater than 8 m/s characterized the entire period, but faster winds (>14 m/s) were associated with cooler temperatures. The overall 80/50 m wind shear was **0.13** for the study period. Wind shear decreased above 80 m.

3.6.2 Site Description

Sodar measurements were made in the San Gorgonio Pass in southern California. The location and period of measurement are given in Table 20.

Table 20: Location and dates of the San Gorgonio sodar study

Name	Latitude	Longitude	Elevation	Start	End
San Gorgonio	33.91906	-116.65431	374m	5/13/2004	6/9/2004

The sodar study area is in a broad dry valley just S of Interstate Highway 10, between two mountain ranges. To the W of the sodar is a homestead with low conifers (Figure 73), but otherwise the site is relatively flat with very low vegetation, with sparse low shrubs (Figure 74 and Figure 75).

3.6.3 Results

At the San Gorgonio site, the overall availability of the sodar was 99%. Of the 3517 wind profiles analyzed after additional filtering, 3360 were qualified samples on the basis of having 50 m wind speeds $\geq$ 5 m/s. Table 21 presents a summary of wind speed and wind shear statistics for all profiles, and by wind direction sector, over the measurement period.

Table 21: Mean statistics for the San Gorgonio sodar study, by wind direction sector. Sectors with fewer than 10 observations are omitted.

Direction	All	E	SE	SW	W	NW
U@30 m	12.4	3.6	3.5	8.4	12.8	9.6
U@50 m	13.2	3.7	3.6	8.6	13.7	10.1
U@80 m	13.9	3.4	3.6	8.7	14.4	10.4
U@110 m	14.1	2.7	3.4	8.9	14.6	10.3
U@120 m	14.1	2.7	3.3	8.9	14.6	10.3
U@140 m	14.1	2.9	3.2	9.0	14.6	10.3
Shear (50/30 m)	0.13	0.04	0.07	0.05	0.13	0.10
Shear (80/50 m)	0.11	-0.16	0.02	0.03	0.12	0.07

Shear (110/80 m)	0.03	-0.70	-0.21	0.04	0.04	-0.04
Number of Profiles	3517	62	51	17	3292	83

Table 22 differentiates shear exponents by wind direction sector for winds $\geq$ 5 m/s, while Table 23 does the same for even windier cases of speeds $\geq$ 8 m/s at 50 m. Mean shear values for the tower and sodar are given. The mean speeds as a function of wind direction at 30 m, 50 m, 80 m and 110 m are also given in
Table 22 and Table 23.

Table 22: Mean statistics for the San Gorgonio sodar study by direction, for 50 m sodar speeds $\geq$ 5 m/s.
Sectors with fewer than 10 observations are omitted.

Direction	All	E	SE	SW	W	NW
U@30 m	12.8	5.3	5.7	12.1	12.9	10.2
U@50 m	13.7	5.4	5.6	12.4	13.8	10.8
U@80 m	14.4	4.9	5.4	12.5	14.6	11.2
U@110 m	14.6	4.0	4.5	12.1	14.8	11.2
U@120 m	14.6	4.0	4.1	12.1	14.8	11.2
U@140 m	14.6	4.1	4.1	12.4	14.8	11.1
Shear (50/30 m)	0.13	0.01	-0.01	0.04	0.13	0.11
Shear (80/50 m)	0.12	-0.18	-0.08	0.01	0.12	0.08
Shear (110/80 m)	0.03	-0.66	-0.61	-0.09	0.04	-0.01
Number of Profiles	3360	14	12	11	3248	75

Table 23: Mean statistics for the San Gorgonio sodar study by direction, for 50 m sodar speeds $\geq$ 8 m/s

Direction	All	SW	W	NW
U@30 m	13.3	12.8	13.3	12.0
U@50 m	14.2	13.1	14.2	12.7
U@80 m	15.0	13.2	15.0	13.3
U@110 m	15.2	12.9	15.2	13.3
U@120 m	15.2	12.8	15.2	13.3
U@140 m	15.2	13.1	15.3	13.0
Shear (50/30 m)	0.13	0.05	0.13	0.11
Shear (80/50 m)	0.12	0.02	0.12	0.10
Shear (110/80 m)	0.04	-0.08	0.04	0.00
Number of Profiles	3126	10	3066	50

Figure 76 and Table 42 in the Appendix summarize the mean speeds and shear by hour of day and by wind speed, respectively.

The wind rose (Figure 77) during the San Gorgonio sodar study period shows the predominance of strong W and WNW winds during this time. The mean speed at 80 m was 13.9 m/s. The wind profiles (Figure 78 through Figure 81) illustrate the low shear, which is consistent with the relatively low uniform vegetation. There is a decrease in the shear above 80 m. The shears were lowest at mid-day and in the early afternoon (Figure 76). Some slightly negative shears occurred for the upper wind profile at lower wind speeds, and easterly winds had substantially negative shears, although the number of observations in that sector was low.

Although the wind direction was nearly constantly westerly during the 30-day study period, there were two wind regimes exhibited, associated with different temperatures recorded at the Palm Springs airport. Cooler temperatures were associated with higher wind speeds (15-16 m/s), while slower winds (8-11 m/s) brought hotter temperatures (Figure 82). The periods of hotter temperatures and slower winds also had intermittent periods of weaker E and SE winds. Large scale thermal contrasts in relation to large-scale pressure gradient apparently cause this change in regime.

The wind direction turned slightly clockwise after sunset each day, becoming WNW by about 2200 LST and accelerating slightly at 80 m, as the surface cooled and created a stable temperature profile. The highest shears (0.17 to 0.18) were found during this period.

Because of the persistent high wind speeds, the flow inclination (vertical velocity/horizontal) was near zero at all heights.

3.6.4 Conclusions

The sodar study in the San Gorgonio Pass has provided information on the shear profile in this broad valley. Winds were consistently from the W during the study period, turning slightly to the WNW in the hours after sunset in response to the Coriolis force, as the flow became less influenced by friction with the surface. The overall 80/50 m shear was **0.13**, but it varied by hour of day between 0.05 in the afternoon and 0.18 at night. The shear decreased above 80 m to an overall value of 0.07. Due to the predominance of winds from the W (98% of the observations with speeds $\geq$ 5 m/s), information about the shear for other wind direction sectors is sparse.

During the 30-day study period two distinct wind speed regimes were noted: one was characterized by cooler temperatures and faster winds, while the reverse conditions pertained in the other. Westerly winds prevailed during both regimes.

3.7 Shasta Valley Sodar Campaign

3.7.1 Summary

A sodar study during the Spring of 2004 at a site in the Shasta Valley has determined shear parameters and other wind characteristics from 30 m to 200 m height above the ground. The site was located in a broad valley west of Mt. Shasta. The energy-containing winds were dominated by winds from the SE and SSE. The study period was characterized by weak winds punctuated by episodes of strong southeasterly winds, with speeds of 4.9 m/s at 80 m. The overall 80/50 m wind shear was 0.06 for the study period.

3.7.2 Site Description

Sodar measurements were made in the Shasta Valley in northern California. The location and period of measurement are given in Table 24.

Table 24: Location and dates of the Shasta Valley sodar study

Name	Latitude	Longitude	Elevation	Start	End
Shasta	41.47917	-122.45311	893m	4/6/2004	5/12/2004

The sodar was operates at the Weed, CA airport. The site is quite flat and open (Figure 83) although the peak of Mt. Shasta (4,318m) dominates the view. Other mountain ranges to the southwest and west have peaks from 2,400 m to 3,000 m.

3.7.3 Results

At the Shasta site, the overall availability of the sodar was 98%. The study period was characterized by weak winds punctuated by episodes of strong southeasterly winds (Figure 84). These disturbed periods were associated with low pressure systems in the northern Pacific Ocean. In these periods, the wind was constantly from the SE, with no diurnal pattern to the wind direction. The mean 50 m wind speeds during the disturbed periods were 10.5 m/s. Table 25 presents a summary of wind speed and wind shear statistics for all profiles, and by wind direction sector, over the measurement period.

Table 25: Shasta sodar mean speeds (“U”) and shear parameters (m) at specified heights by direction

Direction	All	N	NE	E	SE	S	SW	W	NW
U@30 m	4.7	2.6	2.2	2.0	9.2	4.7	2.7	2.8	2.5
U@50 m	4.8	2.7	2.3	1.6	9.5	4.6	2.2	2.8	2.6
U@80 m	4.9	2.9	2.4	1.4	9.8	4.3	2.1	3.0	2.9
U@110 m	5.0	3.1	2.8	1.7	10.0	4.2	2.2	3.1	3.0
U@120 m	5.0	3.1	2.8	1.7	10.0	4.2	2.2	3.1	2.9
U@140 m	4.8	2.8	2.8	1.8	10.0	4.1	2.0	2.5	2.6
Shear (50/30 m)	0.03	0.09	0.03	-0.47	0.07	-0.04	-0.36	0.02	0.11
Shear (80/50 m)	0.06	0.16	0.17	-0.27	0.06	-0.15	-0.13	0.14	0.19
Shear (110/80 m)	0.08	0.17	0.41	0.56	0.05	-0.07	0.17	0.14	0.11
Number of Profiles	4630	801	217	95	1267	648	178	534	890

Seventy-one percent of sodar observations with 50 m wind speed $\geq$ 5 m/s had southeasterly winds (

Table 26). These cases represented 22% of the total sodar observations, and more than 80% of the total power in the wind during the period (Figure 85). Sodar observation with 50 m speeds $\geq$ 8 m/s are shown in Table 27.

Table 26: Shasta sodar mean speeds ("U") and shear parameters at specified heights (m) by wind direction sector, for 50 m sodar speeds > 5 m/s

Direction	All	N	NE	E	SE	S	SW	W	NW
U@30 m	9.7	5.7	6.3		10.9	7.8	7.1	7.7	7.0
U@50 m	10.2	6.1	6.8		11.5	8.3	7.4	7.9	7.2
U@80 m	10.6	6.5	7.5		12.0	8.7	7.5	8.0	7.3
U@110 m	10.9	6.6	8.1		12.3	8.8	6.9	8.1	7.1
U@120 m	10.9	6.6	8.3		12.4	8.8	6.7	8.1	7.1
U@140 m	10.9	6.2	8.4		12.4	8.8	6.6	7.9	7.2
Shear (50/30 m)	0.10	0.13	0.16		0.10	0.12	0.07	0.05	0.06
Shear (80/50 m)	0.09	0.12	0.20		0.09	0.10	0.02	0.02	0.02
Shear (110/80 m)	0.06	0.07	0.24		0.08	0.04	-0.24	0.04	-0.10
Number of Profiles	1493	71	17		993	222	19	74	97

Table 27: Shasta sodar mean speeds ("U") and shear parameters at specified heights (m) by direction, for 50 m speeds > 8 m/s

Direction	All	N	NE	E	SE	S	SW	W	NW
U@30 m	11.3				11.6	9.9		8.9	8.6
U@50 m	11.8				12.2	10.5		9.0	8.9
U@80 m	12.4				12.7	11.0		9.1	8.8
U@110 m	12.7				13.1	11.2		9.1	8.5
U@120 m	12.8				13.2	11.4		9.1	8.5
U@140 m	12.9				13.3	11.5		9.1	8.6
Shear (50/30 m)	0.10				0.10	0.12		0.02	0.05
Shear (80/50 m)	0.09				0.09	0.10		0.01	-0.02
Shear (110/80 m)	0.08				0.09	0.06		0.00	-0.10
Number of Profiles	1028				861	103		31	22

The undisturbed periods were characterized by weak winds overall, with a well-defined diurnal cycle in the wind direction (Figure 86) consistent with the thermally-driven circulations common in the West [2]. Winds during the undisturbed periods were from the SE at night, turning to the SW in the early morning hours. An abrupt shift to northerly then northwesterly winds occurred at 1000 hours. The fastest wind speeds occurred in late afternoon under this regime, but were only 5 m/s at 50 m.

The shear at the site was quite low, 0.05 to 0.10 during the day and 0.15 at night; cases where the 50 m wind speed was > 5 m/s (disturbed cases) had mean shear of 0.10.

Average wind profiles and shear parameters are shown in Figure 87 to Figure 90. Mean speeds and shears parameters by hour of day and speed are provided in Figure 91 and Table 43 respectively.

[2] Stewart, J.Q., C. D. Whiteman, W. J. Steenburgh, and X. Bian. 2002. A climatological study of thermally driven wind systems of the U.S. intermountain west. Bull. Am. Met. Soc. May 2002 699-708.

A meteorological monitoring station located at the airport about 140 m W of the sodar (Figure 92) is operated by the California Department of Water Resources. The anemometer at this site appears to be at about 3 m height. Hourly data from this station for the period from April 1, 2003 to May 15, 2004 were obtained from the California Data Exchange Center website of the Department of Water Resources.

Comparison of daily mean speeds with those from an anemometer at 3 m, at a met station 140 m to the west of the sodar gave these results:

Sodar at 30 m = 0.1608 + 1.22*MetStn(3m), R^2=0.98
Sodar at 50 m =-0.25+1.43*MetStn(3m), R^2=0.98
Sodar at 80 m =-0.46+1.53*MetStn(3 m); R^2=0.97

An example of the comparison of sodar with meteorological station data is shown in Figure 93.

The annual mean wind speed at the met station (at 3 m) was 3.45 m/s; using the above regression equations to scale the sodar speed to the Met Station record, we obtain 4.37 m/s at 30 m, 4.68 m/s at 50 m, and 4.82 m/s at 80 m. The met. station anemometer had hourly winds 5 m/s or greater 23.7% of the time during the previous year, and more than 50% of those cases were on SE winds. The modeled 70 m annual mean wind speed at that location is 5.16 m/s.

Flow inclination was near zero for every wind direction and throughout the vertical profile.

3.7.4 Conclusions

The sodar study in the Shasta Valley provided information on the shear profile in this broad valley. The only ongoing meteorological measurements available were from a California Depart of Water Resources met station located within 200 m of the sodar. The study period was characterized by weak winds punctuated by episodes of strong southeasterly winds. The overall 80/50 m shear was **0.06**, but it depended on time of day, from –0.05 to 0.22, with the highest shear in the early evening. Using the sodar measurements and the California Depart of Water Resources 3 m met station as a long-term reference, an 80 m speed of 4.82 m/s is predicted for the site.

4.0 Review of Measurement Program Results

In a previous project for the California Energy Commission entitled “New Wind Energy Resource Maps of California,” AWS Truewind identified several issues affecting the accuracy of the wind resource maps. The following recommendations were presented to improve the accuracy of the maps:

- Measure the winds aloft
- Analyze boundary layer issues
- Produce high-resolution modeling of selected areas
- Improve land cover data.

During the measurement program, four tower-years of high-quality tall tower data was collected as well as over five months of sodar data at heights up to 200 m. As discussed below, this contributed directly to the recommendations of the previous project, except the need to improve land cover data, as this was not include in the scope of this project.

To assist with high-resolution modeling of selected areas, four high-quality, climatologically adjusted validation datasets were produced at within the areas selected for high-resolution modeling. While most of the validation points used in the previous validation were less than 20m, the measurement program provided top-level measurement heights above 60m, with three towers above 80 m and two above 100 m.

The measurement program characterized the development of the nocturnal boundary layer at heights relevant to modern wind turbines. The impact of the boundary layer are seen in the plots of tall tower diurnal speed distributions (Figure 3) as well as the diurnal sodar statistics (Figure 16, Figure 25, Figure 46, Figure 60, Figure 66, Figure 76 and Figure 91). The temperature profile data collected at Oak Creek and Transtower also provide important boundary layer data (Figure 5). Together, the tall tower and sodar data serve as the primary input to the Boundary Layer Research task.

The sodar was sited in the vicinity of meteorological stations at Antelope Valley, Oak Creek, and Shasta Valley. Only the Oak Creek site allows comparison of sodar and tower measurements, as the Antelope Valley and Shasta sites were equipped with short towers, 21 m and 3m respectively, while sodar begin at 30 m. Though the Oak Creek tower and sodar were 100m apart, the regression of hourly-averaged 70 m sodar and tower measurements yielded a slope of 0.87 and an intercept of 1.05 m/s, with an R^2 of 0.80. However, local terrain and turbine wakes are apparent in the shear, flow inclination and turbulence intensity profiles. These results are consistent with other comparisons between sodar measurements and tower measurements at complex sites. When tall tower and sodar data are compared at simpler sites, where terrain and turbine wakes do not produce different flows at the sodar and tower locations, measurements typically agree within the accuracy level of the two technologies. Sodar measurements in complex terrain and at heights above standard meteorological towers will be valuable to the Boundary Layer Research task.

Appendix

Table 28: Tall Tower anemometer information

Oak Creek

Anemometer	Anem 1	Anem 2	Anem 3	Anem 4	Anem 5	Anem 6
Instrument Manufacturer	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.
Instrument Model	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C
Monitoring Height	88.4 m	88.4 m	70.1 m	70.1 m	52.7 m	52.7 m
Primary or Redundant?	Redundant	Primary	Primary	Redundant	Redundant	Primary
Mounting Boom Orientation	233^{o} TN	53^{o} TN	53^{o} TN	233^{o} TN	233^{o} TN	53^{o} TN
Calibration Slope (m/s / Hz)	0.7602	0.7623	0.7701	0.7636	0.7641	0.7613
Calibration Offset (m/s)	0.456	0.455	0.302	0.404	0.477	0.436
Logger Channel Number	1	2	3	4	5	6

Rosamond

Anemometer	Anem 1	Anem 2	Anem 3	Anem 4	Anem 5	Anem 6
Instrument Manufacturer	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.
Instrument Model	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C
Monitoring Height	109.7 m	109.2 m	76.8 m	76.3 m	44.8 m	44.3 m
Primary or Redundant?	Primary	Redundant	Primary	Redundant	Primary	Redundant
Mounting Boom Orientation	314^{o} TN	134^{o} TN	314^{o} TN	134^{o} TN	314^{o} TN	134^{o} TN
Calibration Slope (m/s / Hz)	0.7592	0.7551	0.7572	0.7681	0.7617	0.7630
Calibration Offset (m/s)	0.473	0.496	0.383	0.361	0.458	0.456
Logger Channel Number	1	2	3	4	5	6

Transtower

Anemometer	Anem 1	Anem 2	Anem 3	Anem 4	Anem 5	Anem 6
Instrument Manufacturer	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.
Instrument Model	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C
Monitoring Height	111.3 m	111.3 m	84.7 m	84.7 m	46.1 m	46.1 m
Primary or Redundant	Primary	Redundant	Primary	Redundant	Primary	Redundant
Mounting Boom Orientation	233^{o} TN	53^{o} TN	53^{o} TN	233^{o} TN	233^{o} TN	53^{o} TN
Calibration Slope (m/s / Hz)	0.7643	0.7578	0.7571	0.7689	0.7680	0.7570
Calibration Offset (m/s)	0.443	0.452	0.445	0.357	0.376	0.377
Logger Channel Number	1	2	3	4	5	6

Geyserville

Anemometer	Anem 1	Anem 2	Anem 3	Anem 4	Anem 5	Anem 6
Instrument Manufacturer	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.	NRG Sys.
Instrument Model	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C	Max 40C
Monitoring Height	60.1 m	60.7 m	43.9 m	44.2 m	29.3 m	29.6 m
Primary or Redundant	Primary	Redundant	Primary	Redundant	Primary	Redundant
Mounting Boom Orientation	340^{o} TN	160^{o} TN	340^{o} TN	160^{o} TN	340^{o} TN	160^{o} TN
Calibration Slope (m/s / Hz)	0.7681	0.7657	0.7546	0.7658	0.7688	0.7621
Calibration Offset (m/s)	0.361	0.328	0.425	0.435	0.345	0.378
Logger Channel Number	1	2	3	4	5	6

Table 29: Tall Tower data summary

Wind Characteristic	Oak Creek	Rosamond	Transtower	Geyserville
12 Month Period of Record	7/04 – 6/05	7/04 – 6/05	8/04 – 7/05	7/04 – 6/05
Top Monitoring Height	88.4 m	109.7 m	111.3 m	60.1 m
Observed Mean Wind Speed	7.84 m/s	6.92 m/s	5.91 m/s	5.98 m/s
Wind Speed Data Recovery	98.5 %	90.4 %	98.5 %	99.8 %
Wind Shear Exponent (heights)	0.240 (88/70)	0.240 (110/77)	0.332 (111/85)	0.087 (60/44)
Turbulence Intensity	0.152	0.095	0.104	0.114
Weibull Parameters (A/k)	8.79 m/s / 1.72	7.81 m/s / 1.83	6.62 m/s / 1.72	6.61 m/s / 1.49
Energy Weighted Annual Air Density	1.057 kg/m^3	1.108 kg/m^3	1.221 kg/m^3	1.108 kg/m^3
Annual Wind Power Density	1100 W/m^2	696 W/m^2	513 W/m^2	620 W/m^2
Prevailing Wind / Energy Direction	NW / NW	WSW / SW	WSW / WSW	NNW / NNE

Table 30: Tall Tower monthly mean wind speeds

Month	Oak Creek (88.4 m)		Rosamond (109.7 m)		Transtower (111.3 m)		Geyserville (60.1 m)	
	Wind Speed (m/s)	Data Recovery	Wind Speed (m/s)	Data Recovery	Wind Speed (m/s)	Data Recovery	Wind Speed (m/s)	Data Recovery
May-04	12.02	100 %	N/A	N/A	N/A	N/A	N/A	N/A
Jun-04	12.36	100 %	N/A	N/A	N/A	N/A	6.17	99.9 %
Jul-04	9.01	100 %	8.19	97.1 %	N/A	N/A	3.72	100 %
Aug-04	8.01	100 %	7.68	95.7 %	7.22	100 %	4.65	100 %
Sep-04	8.19	100 %	6.76	90.3 %	6.41	94.2 %	5.74	100 %
Oct-04	6.92	99.6 %	6.71	89.9 %	5.91	100 %	5.94	100 %
Nov-04	6.06	98.2 %	5.25	83.6 %	4.65	99.9 %	6.49	100 %
Dec-04	4.28	94.5 %	5.32	82.0 %	5.03	100 %	7.66	100 %
Jan-05	5.39	95.7 %	5.05	82.6 %	3.99	100 %	6.19	98.3 %
Feb-05	5.88	94.3 %	5.91	87.1 %	4.73	100 %	6.60	100 %
Mar-05	7.70	100 %	7.08	88.3 %	5.73	100 %	7.29	100 %
Apr-05	9.42	100 %	7.91	90.4 %	6.58	100 %	6.12	99.6%
May-05	11.52	99.9 %	7.59	96.0 %	6.64	100 %	5.95	100 %
Jun-05	11.17	99.8 %	8.69	95.4 %	7.18	100 %	5.41	100 %
Jul-05	N/A	N/A	N/A	N/A	6.87	88.5 %	N/A	N/A

Table 31: Tall Tower mean wind shear at top monitoring height, as a function of wind speed

Wind Speed Bin (m/s)	Oak Creek (88.4m)	Rosamond (109.7m)	Transtower (111.3m)	Geyserville (60.1m)
4	0.371	0.420	0.233	-0.003
5	0.328	0.376	0.266	0.017
6	0.302	0.337	0.309	0.069
7	0.288	0.319	0.314	0.088
8	0.263	0.291	0.333	0.103
9	0.242	0.267	0.358	0.122
10	0.231	0.240	0.395	0.124
11	0.226	0.201	0.424	0.115
12	0.218	0.185	0.429	0.116
13	0.209	0.189	0.418	0.111
14	0.203	0.181	0.396	0.108
15	0.200	0.173	0.329	0.092
16	0.192	0.168	0.306	0.083
17	0.191	0.160	0.263	0.073
18	0.187	0.159	0.238	0.067
19	0.177	0.161	0.209	0.061
20	0.167	0.116	0.207	0.059
21	0.153	0.110	0.265	0.061
22	0.154	N/A	0.154	0.045
23	0.159	N/A	0.154	0.054
24	0.163	N/A	0.175	0.067
25	0.154	N/A	N/A	0.052
26	0.166	N/A	N/A	0.067
27	0.227	N/A	N/A	0.030

Table 32: Tall Tower reference site summary

Reference Site	ASOS Commissioning	Annual Mean Wind Speed (m/s)
Sacramento, CA	April 1998	2.80
Santa Rosa, CA	June 1998	2.14
Vacaville, CA	March 1998	2.66
Lancaster, CA	December 2000	4.84
Palmdale, CA	April 1998	4.25

Table 33: Tall Tower reference site regression summary

Monitoring Site	Reference Station	Slope	Intercept	R-squared
Oak Creek	Lancaster	**1.3172**	**1.7533**	**0.6328**
	Palmdale	1.4364	2.1471	0.3996
Rosamond*	Lancaster	0.9730	2.1676	0.7406
	Palmdale	1.3188	1.3185	0.7398
Transtower	Sacramento	**1.6580**	**1.3833**	**0.8163**
	Vacaville	1.4337	2.2550	0.5978
Geyserville	Santa Rosa	**1.7165**	**2.2293**	**0.3190**
	Vacaville	1.0146	3.3272	0.2101

*Since the r-squared values are identical, a multiple linear regression was used. The r-squared of the new relationship is 0.81.

Table 34: Tall Tower long-term wind speed projections

Monitoring Site	Monitoring Height (m)	Wind Speed Projection (m/s)	Mean Wind Shear	70 m Wind Speed Projection (m/s)	100 m Wind Speed Projection (m/s)
Oak Creek	88.4	8.13	0.240	7.67*	8.38
Rosamond	109.7	6.89	0.240	6.16*	6.74
Transtower	111.3	6.03	0.332	5.23*	5.82
Geyserville	60.1	5.90	0.087	5.98	6.17

*The 70 m wind speed projection was derived through shear extrapolation from the middle level anemometer because it was closer to 70 m than the top sensor.

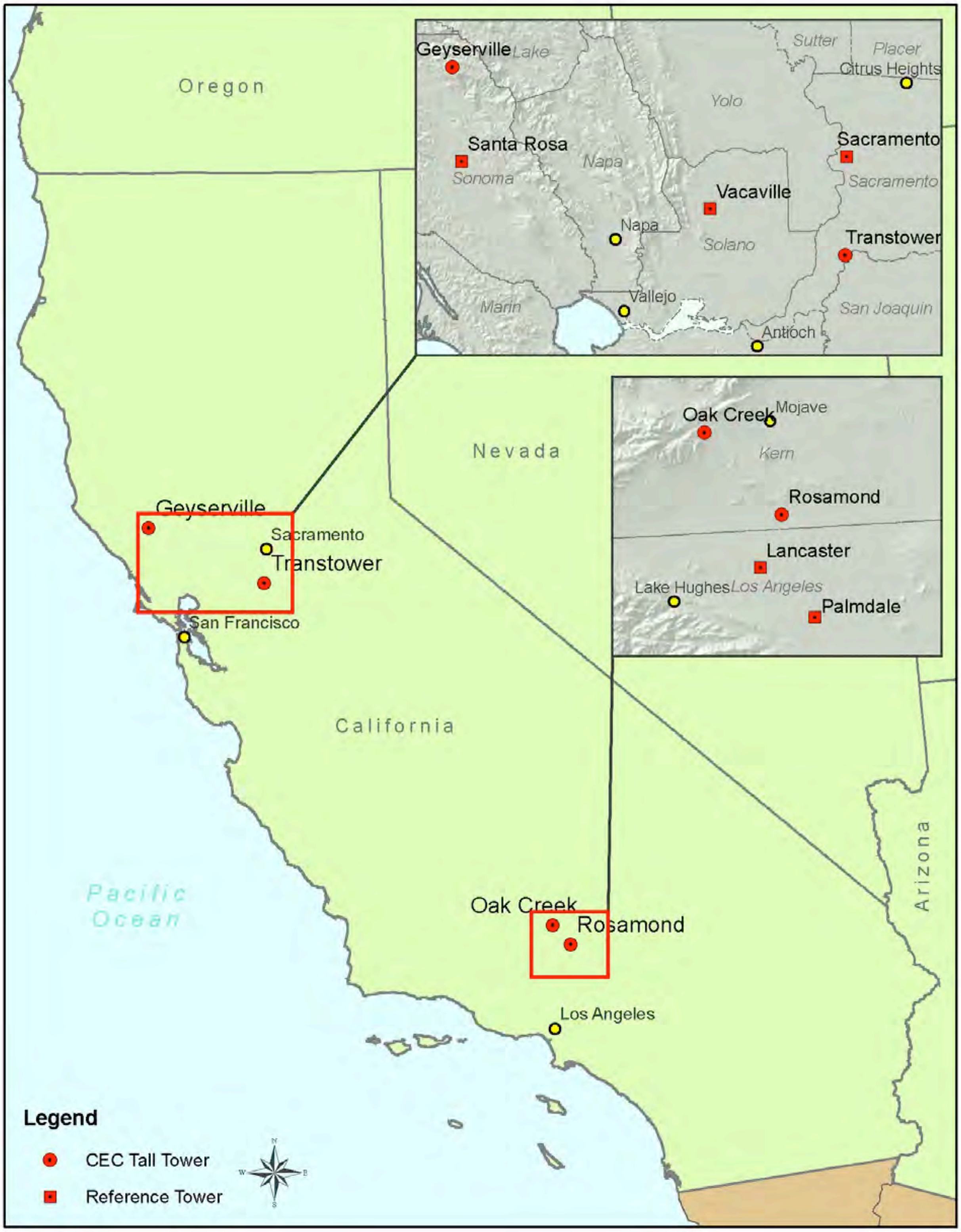
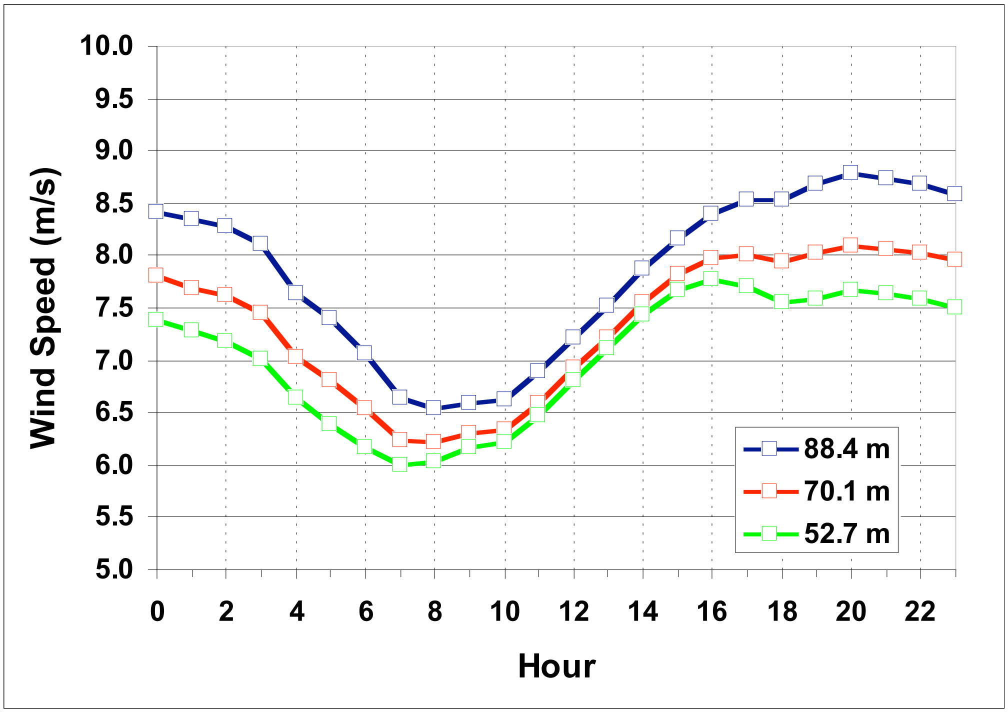
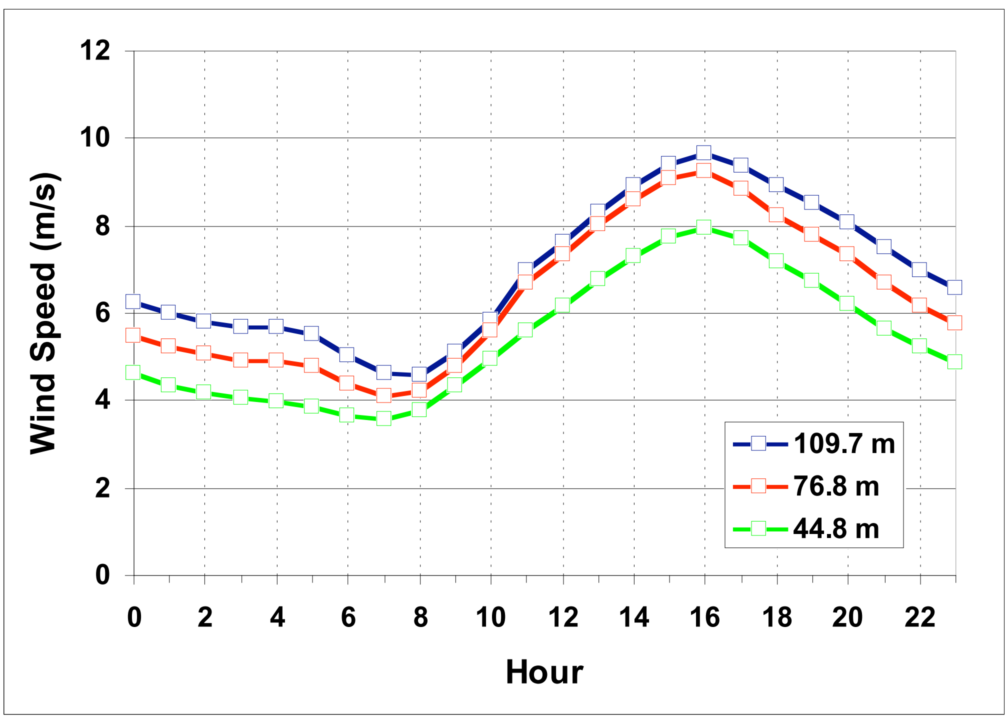


Figure 2: Energy Commission Tall Tower and reference station locations

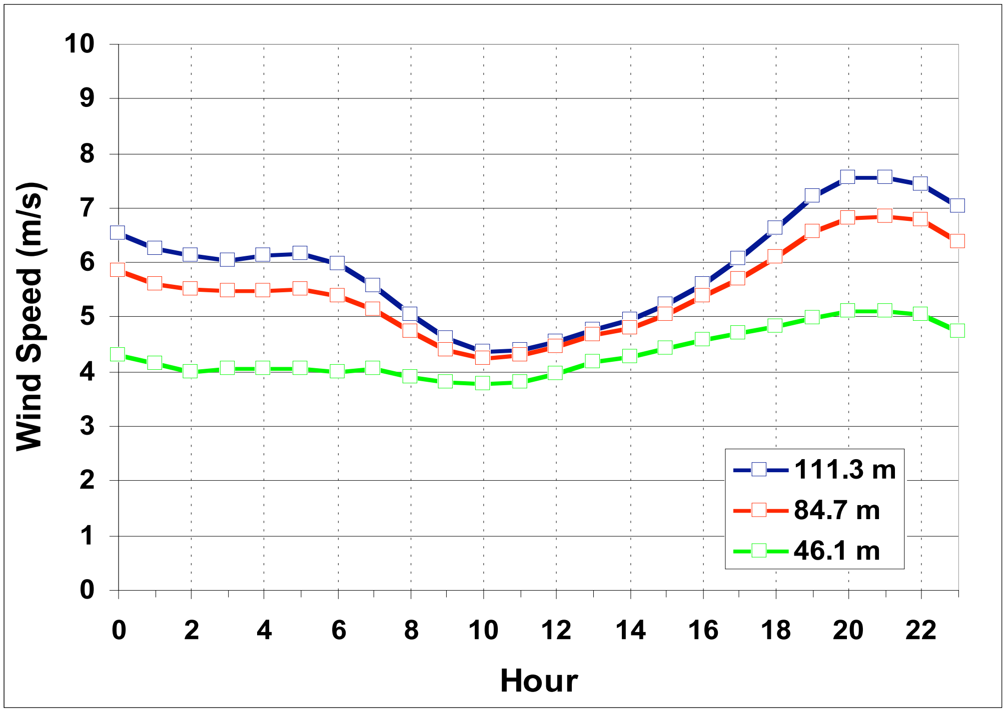
Oak Creek



Rosamond



Transtower



Geyserville

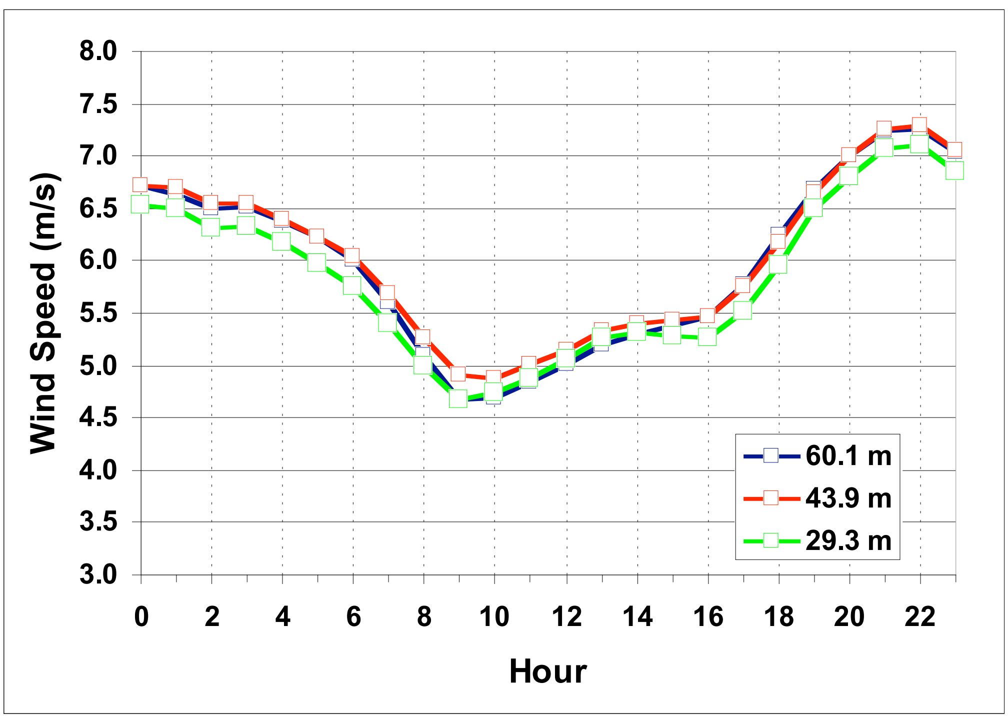
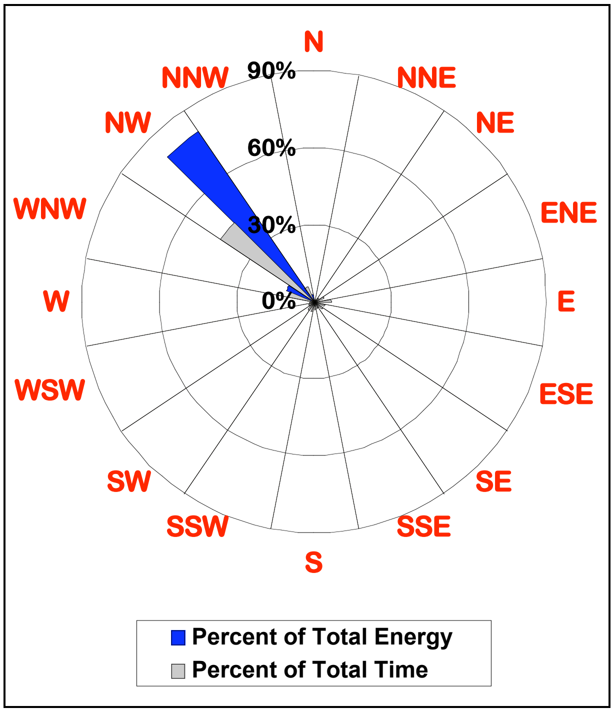
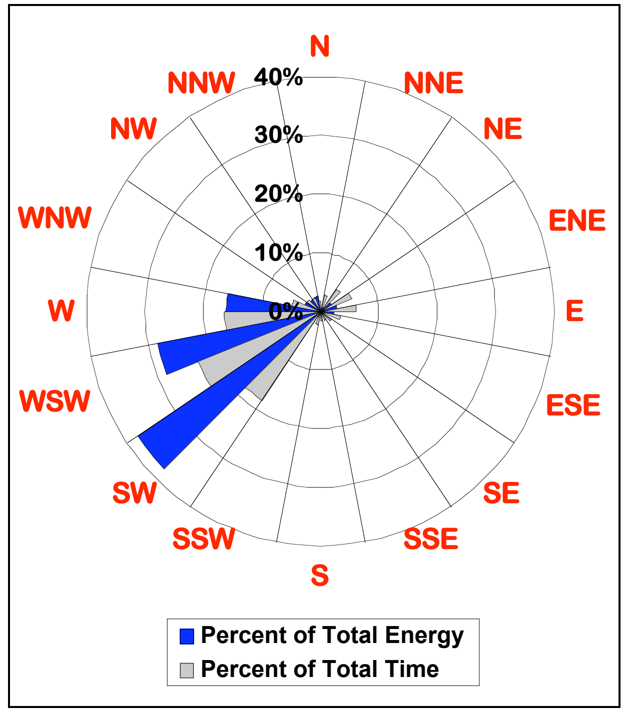


Figure 3: Tall Tower hourly mean wind speed distributions

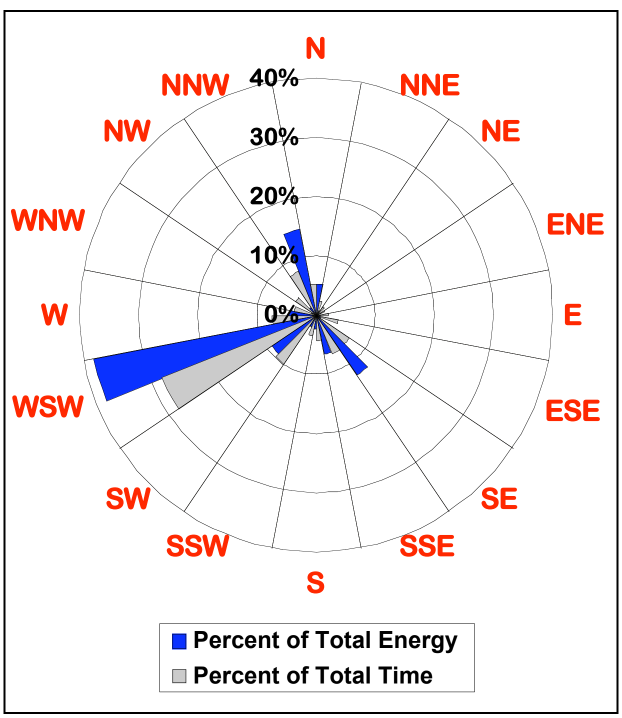
Oak Creek



Rosamond



Transtower



Geyserville

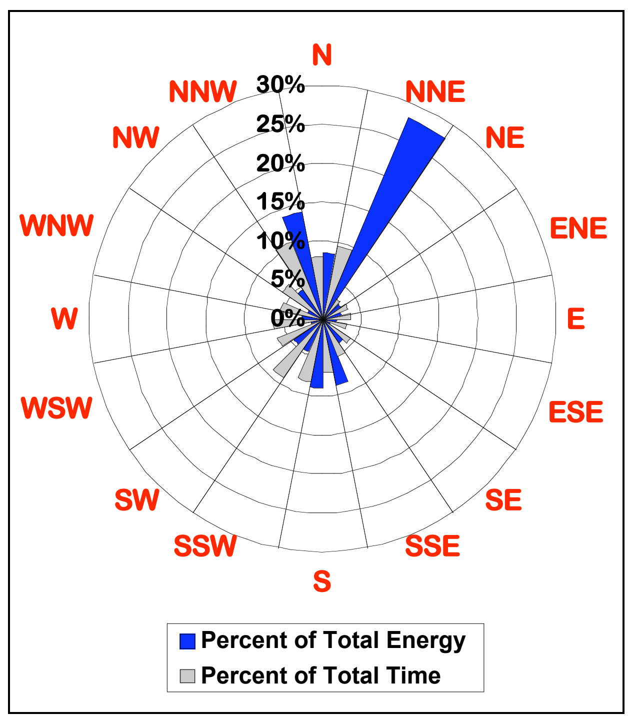
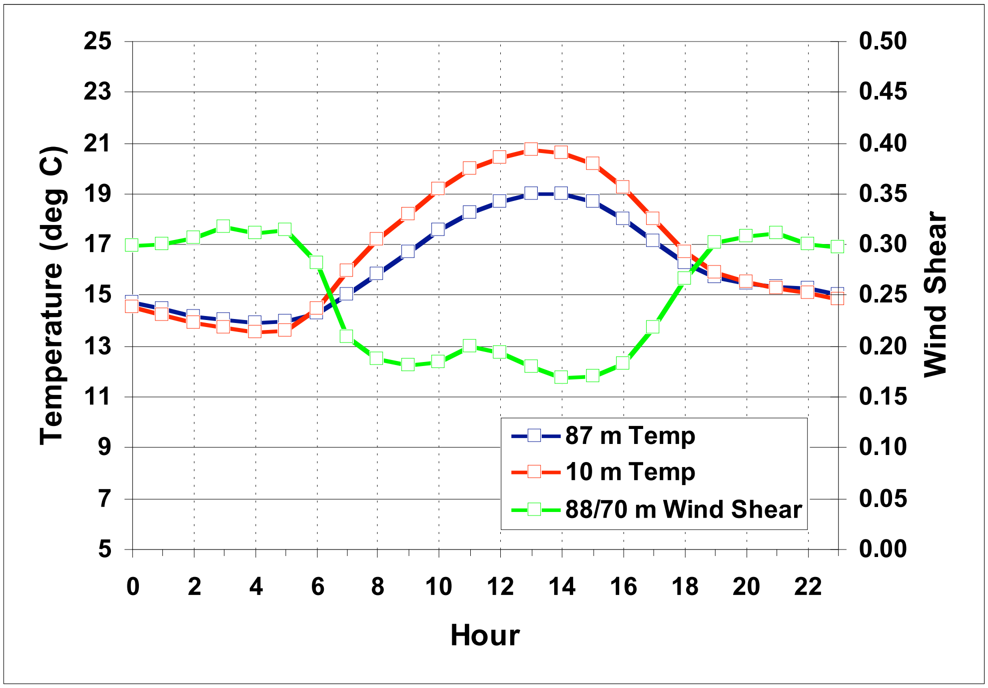


Figure 4: Tall Tower wind roses

Oak Creek



Transtower

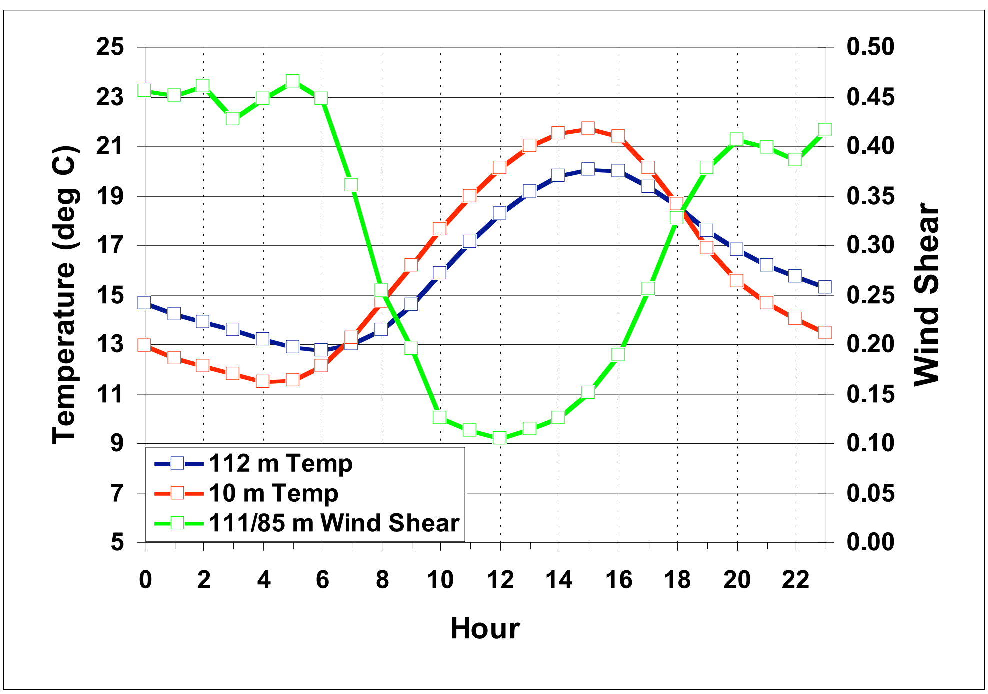


Figure 5: Tall Tower diurnal temperature and wind shear distributions

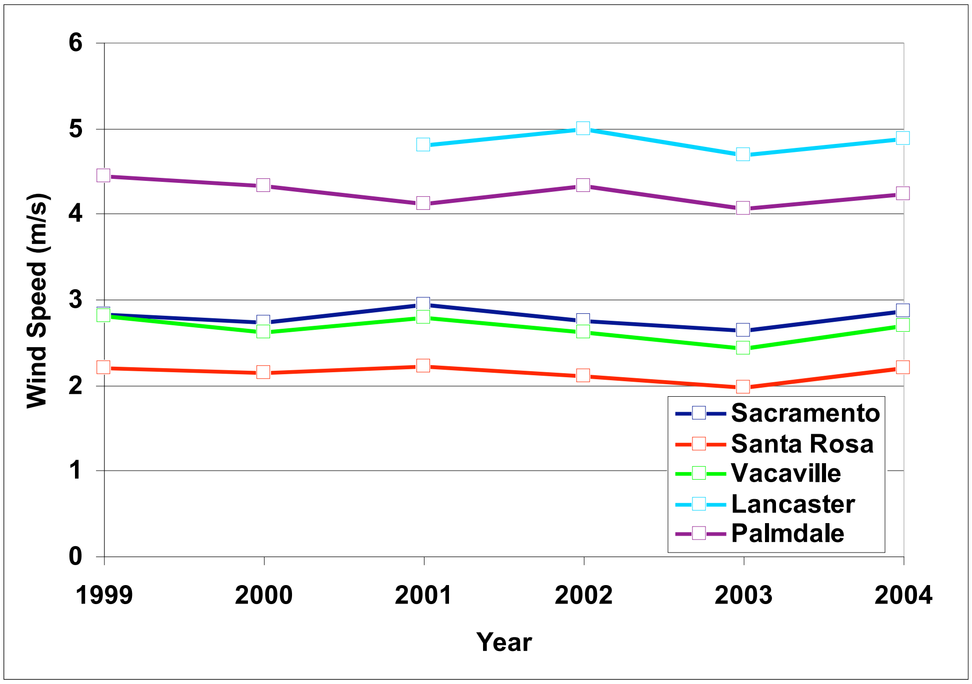


Figure 6: Reference station annual mean wind speeds, for Tall Tower sites

Table 35: Locations and types of sensors on the Rosamond and Oak Creek towers. Cup anemometers at Rosamond were mounted on booms oriented to 300^o (primary) and 120^o (redundant), while those at Oak Creek were oriented to 39^o (primary) and 219^o (redundant).

Instrument	Rosamond Tower Height, m	Oak Creek Tower Height, m
NRG Max 40 cup	110	88
NRG Max 40 cup	77	70
NRG-Max 40 cup	45	53
NRG-200 P Vane	106	85
NRG-200 P Vane	74	74
NRG-200 P Vane	42	52
RMYoung Temperature	5	87
RMYoung Temperature		10
Licor Pyranometer	3.5	3.5

Figure 7: Sodar at Antelope Valley site, looking west

Figure 8: Sodar at Antelope Valley site, looking south

Figure 9: Sodar at Oak Creek site, looking north

Figure 10: Sodar at Oak Creek site, looking south.
The taller meteorological tower is the Oak Creek tower used as a reference in this study.

Figure 11: Sodar at Oak Creek site, looking west

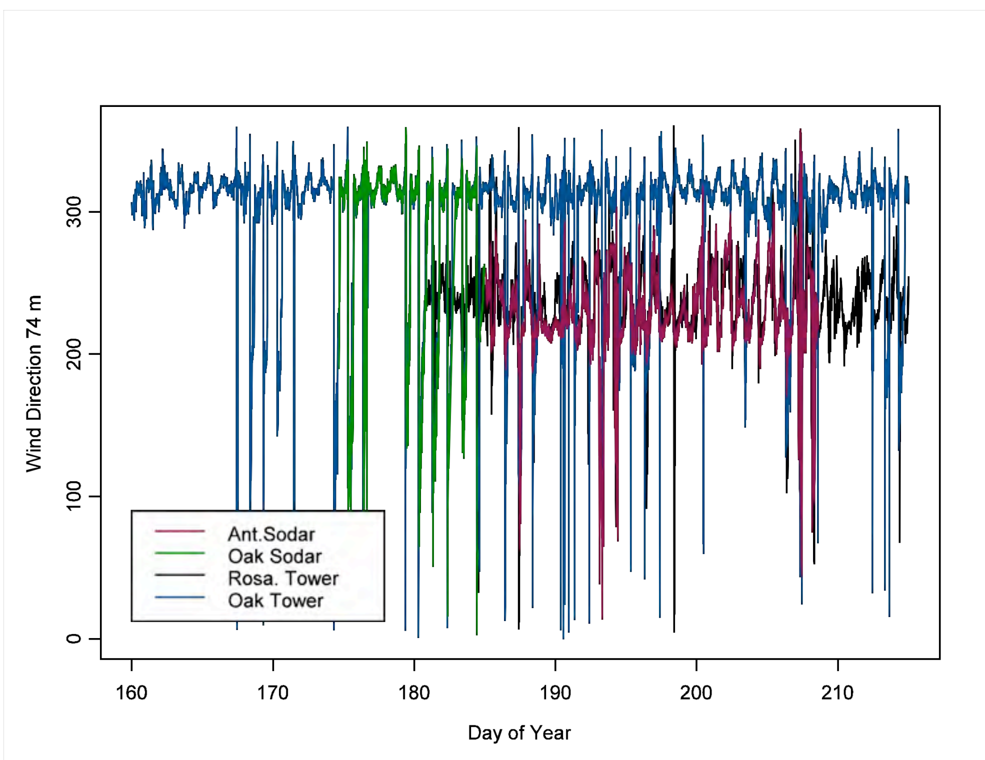


Figure 12: Time series of wind direction, for the Antelope Valley and Oak Creek sodars as well as Rosamond and Oak Creek towers

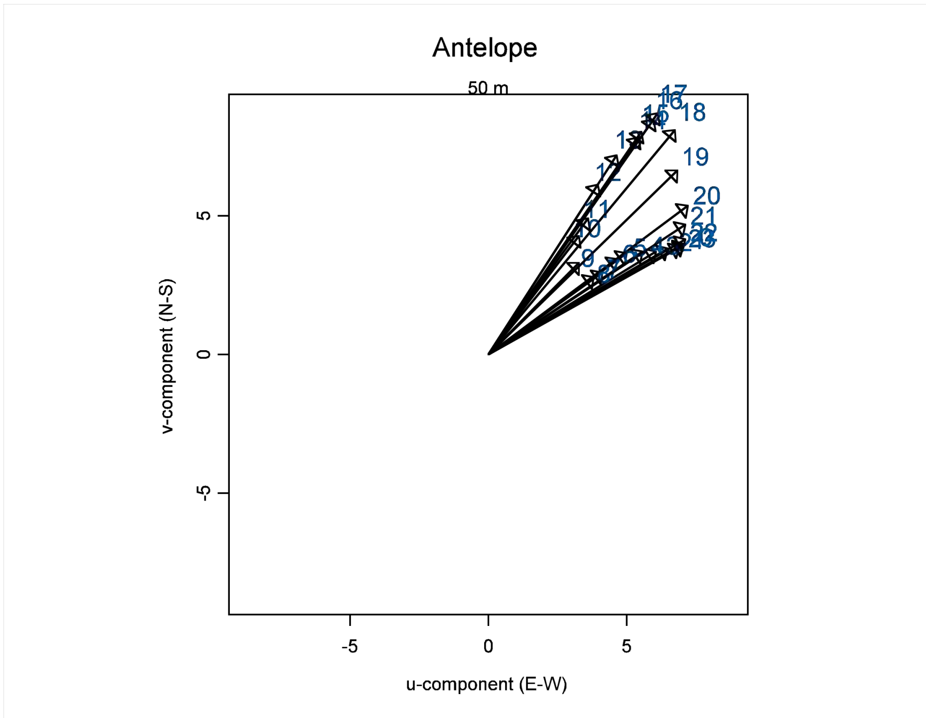


Figure 13: Antelope Valley sodar hodograph, at 50 m. Arrows depict the wind vector for each labeled hour.

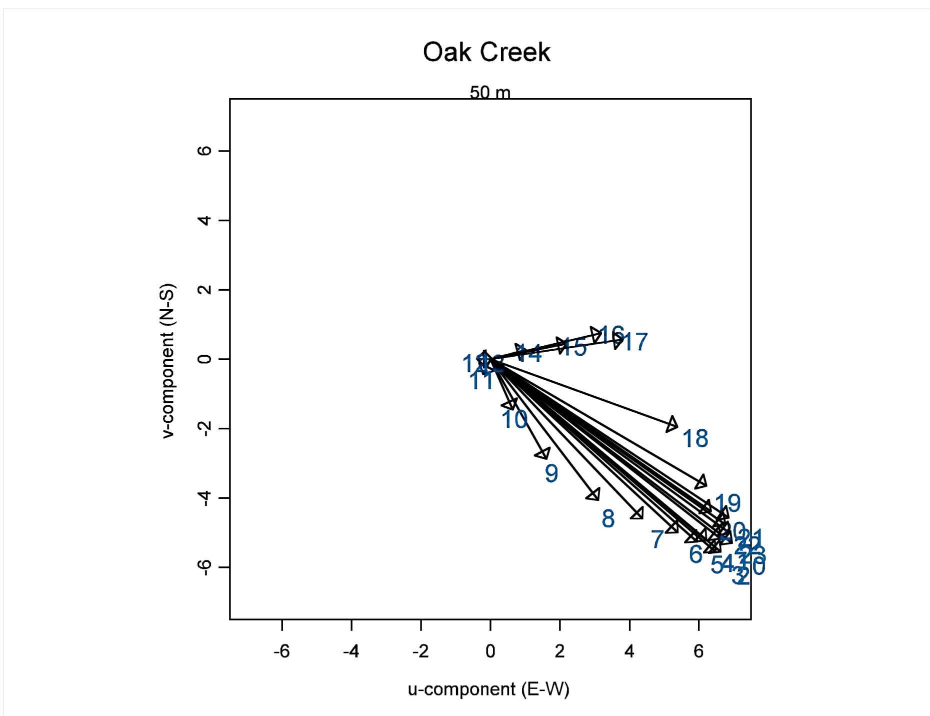


Figure 14: Oak Creek sodar hodograph, at 50 m. Arrows depict the wind vector for each labeled hour.

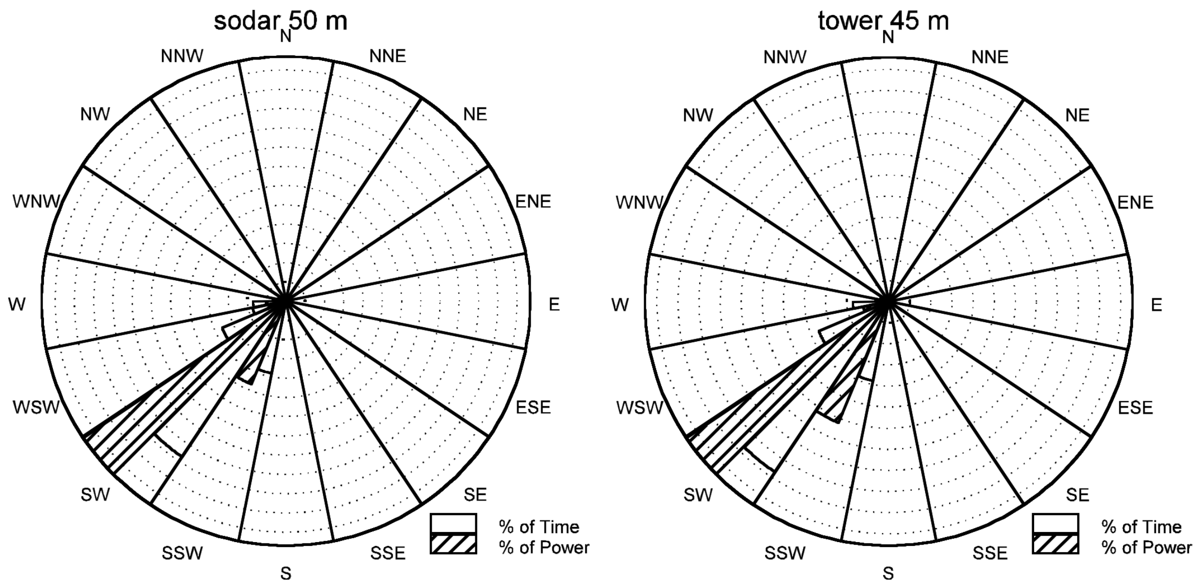


Figure 15: Wind roses for the Antelope Valley sodar site and Rosamond tower, during the Antelope Valley sodar study.
Dotted circles are at increments of 5% beginning with 0% at the center.

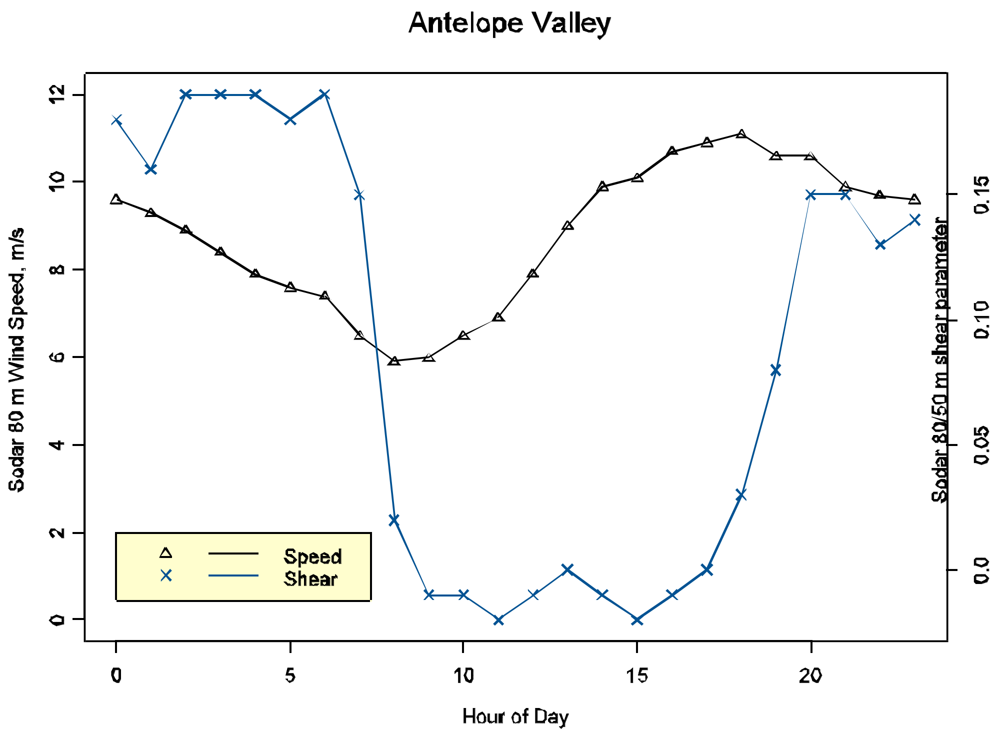


Figure 16: Antelope Valley sodar 80 m speed and 80/50m slope, by time of day

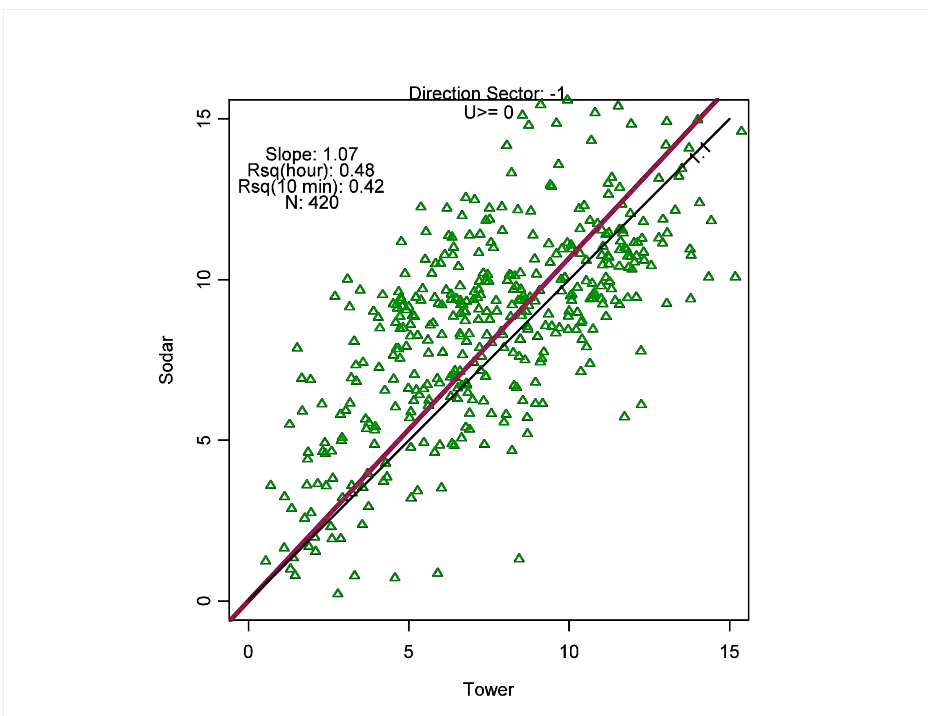


**Figure 17: Hourly average wind speeds for the Antelope Valley sodar and Rosamond tower at 110 m, for all speeds and directions.
The slope is for the line forced through zero.**

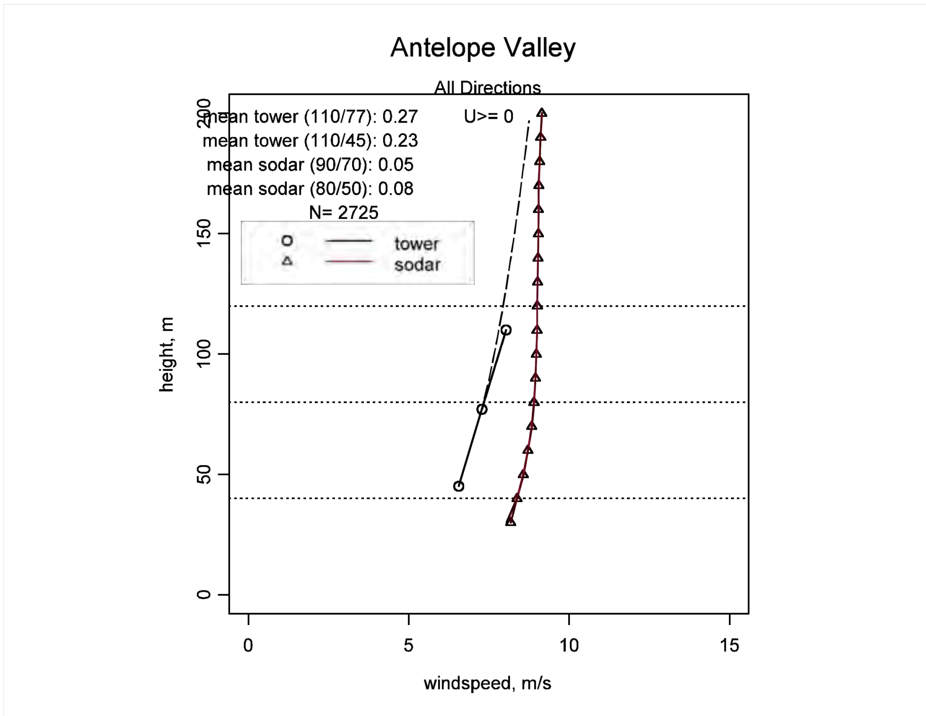


Figure 18: Average wind speed profiles for the Antelope Valley sodar and the Rosamond tower, for all speeds and directions.
The dashed line is the extrapolated tower wind profile using the 77/45 m shear parameter.

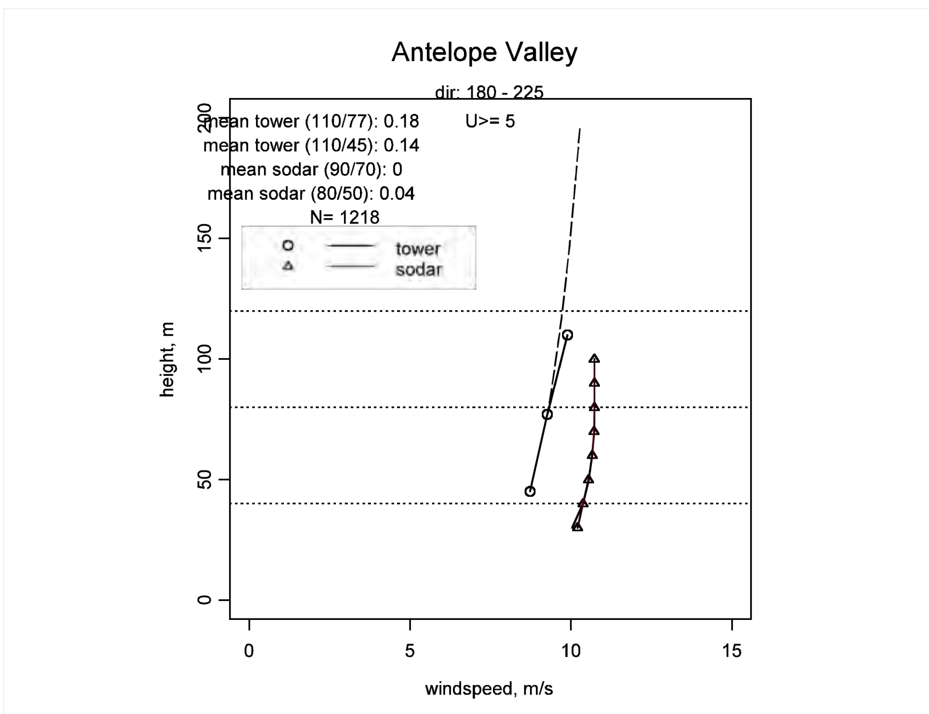


Figure 19: Average wind speed profiles for the Antelope Valley sodar and the Rosamond tower, for 50 m sodar speeds $\geq$ 5 m/s, and wind from the SSW

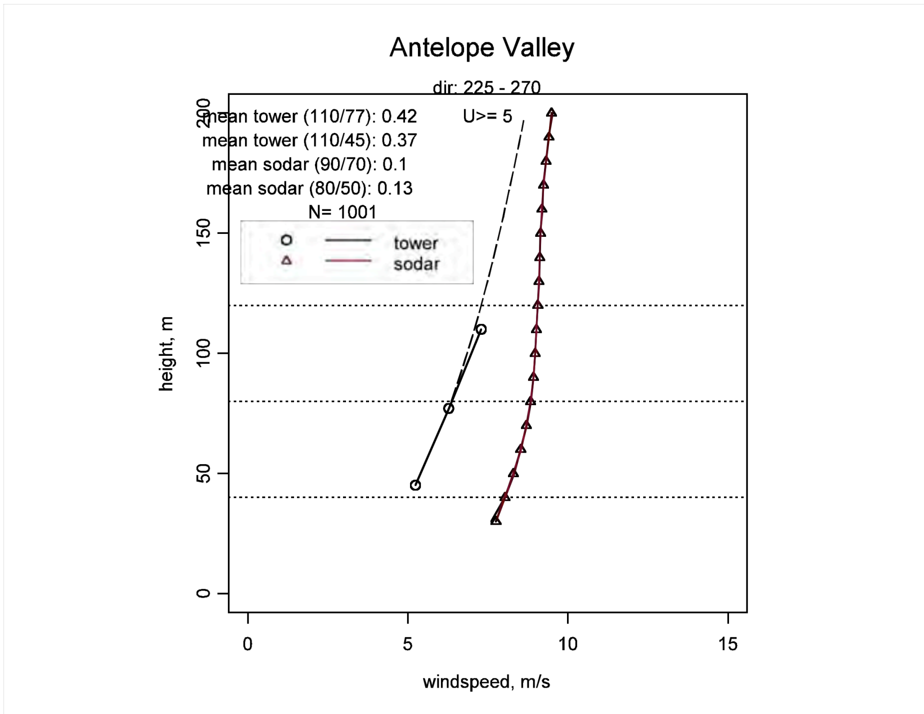


Figure 20: Average wind speed profiles for the Antelope Valley sodar and the Rosamond tower, for 50 m sodar speeds ≥ 5 m/s, and wind from the WSW

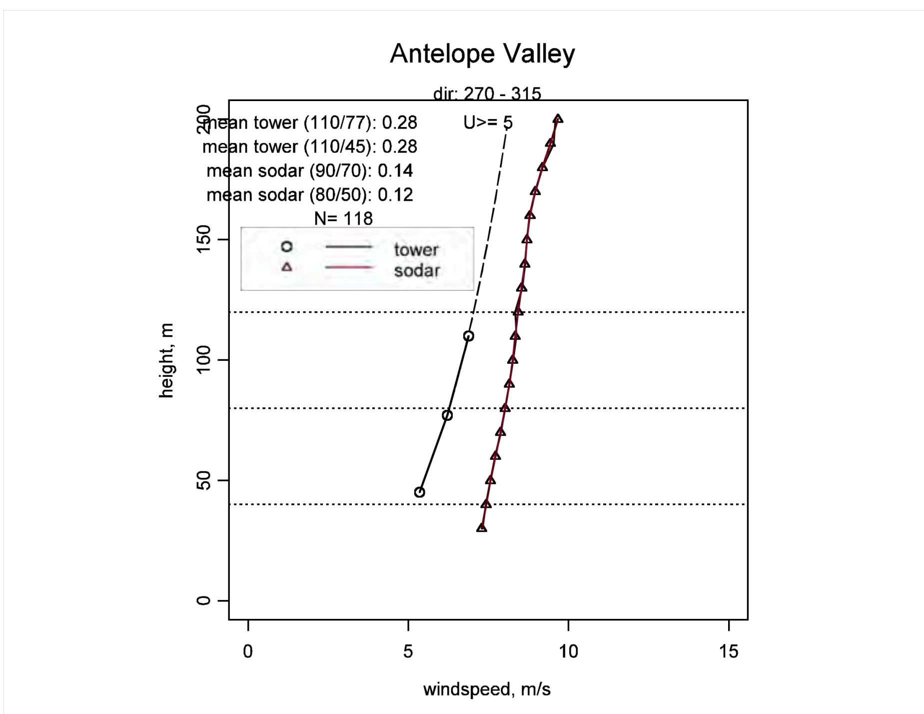


Figure 21: Average wind speed profiles for the Antelope Valley sodar and the Rosamond tower, for 50 m sodar speeds ≥ 5 m/s, and wind from the WNW

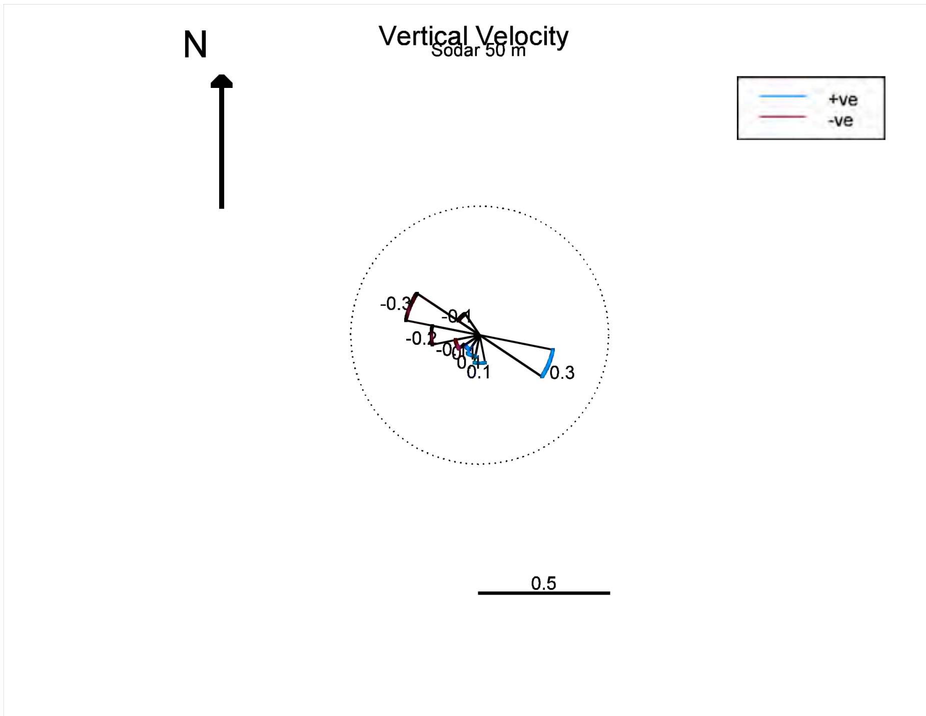


Figure 22: Antelope Valley sodar vertical velocity, at 50 m (positive upward)

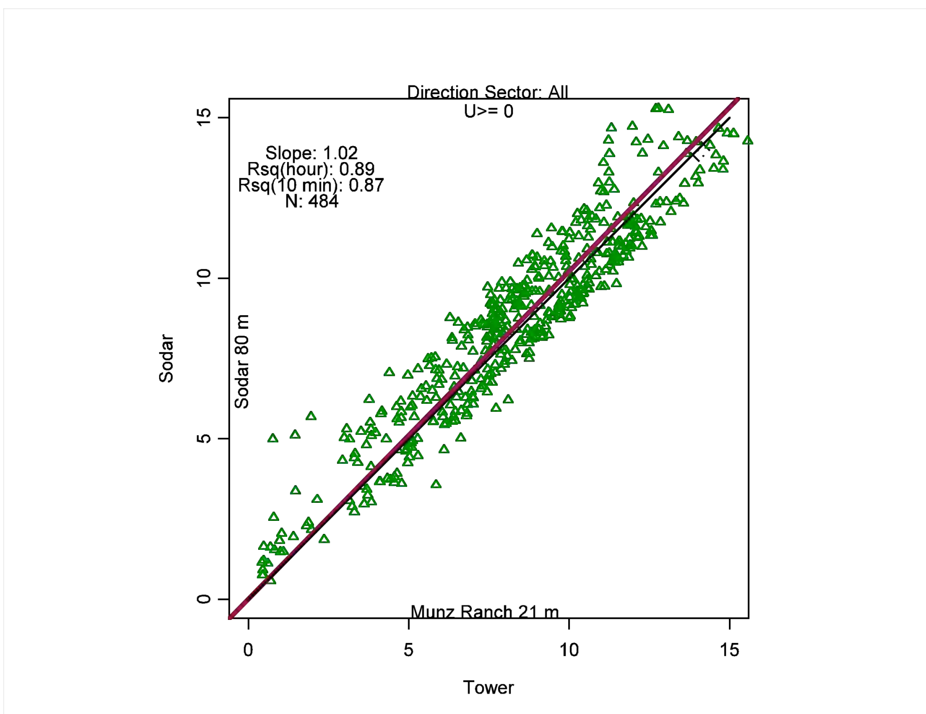


Figure 23: Comparison of hourly Antelope Valley sodar 80 m speed with the Munz Ranch 21 m speed.
The slope is for the line forced through the origin.

Table 36: Mean statistics at specified heights (m) for the Antelope Valley sodar study, by speed (m/s).
Speed bin designations are the lower bound of the bin.

Speed	0	1	2	3	4	5	6	7
U@30 m	0.5	1.4	2.4	3.3	4.3	5.2	6.1	7.1
U@50 m	0.6	1.5	2.5	3.5	4.5	5.5	6.5	7.5
U@80 m	0.8	1.5	2.6	3.8	4.8	5.9	6.8	8.0
U@110 m	0.8	1.5	2.8	4.1	5.0	6.1	7.0	8.2
U@120 m	0.9	1.7	2.9	4.1	5.1	6.2	7.1	8.3
U@140 m	1.4	1.9	2.9	4.1	5.1	6.3	7.2	8.5
Shear (50/30 m)	0.41	0.08	0.09	0.14	0.09	0.12	0.10	0.12
Shear (80/50 m)	0.42	-0.01	0.13	0.20	0.13	0.15	0.12	0.13
Shear (110/80 m)	-0.01	0.16	0.20	0.20	0.15	0.14	0.08	0.09
Number of Profiles @ 50 m	21	71	72	101	170	199	245	323

Speed	8	9	10	11	12	13	14	15	16
U@30 m	8.1	9.0	10.0	11.0	11.9	12.9	13.9	14.7	15.6
U@50 m	8.5	9.4	10.5	11.4	12.4	13.5	14.5	15.4	16.3
U@80 m	8.9	9.7	10.7	11.6	12.8	14.1	15.0	16.1	16.7
U@110 m	9.0	9.6	10.6	11.6	12.9	14.3	15.2	16.5	16.7
U@120 m	9.0	9.6	10.5	11.5	12.9	14.4	15.2	16.5	16.7
U@140 m	9.0	9.6	10.3	11.3	12.9	14.4	15.2	16.3	16.7
Shear (50/30 m)	0.10	0.08	0.08	0.07	0.09	0.09	0.07	0.09	0.08
Shear (80/50 m)	0.09	0.06	0.04	0.04	0.08	0.09	0.07	0.10	0.05
Shear (110/80 m)	0.03	-0.02	-0.04	-0.02	0.02	0.05	0.04	0.08	0.02
Number of Profiles @ 50 m	390	324	345	288	134	93	62	37	18

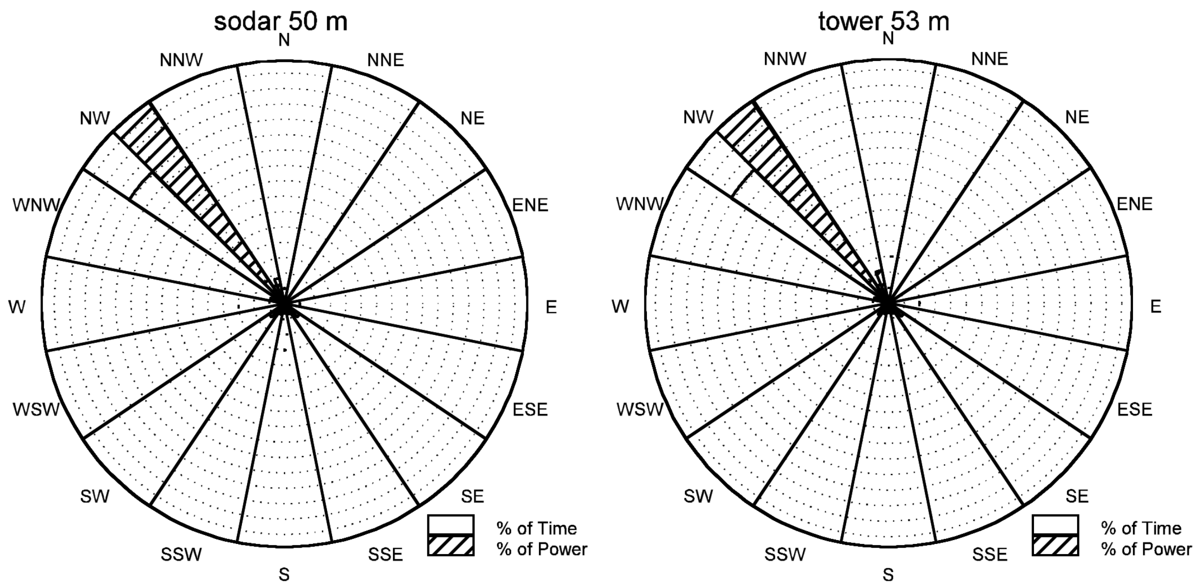


Figure 24: Wind roses for the Oak Creek sodar and tower during the Oak Creek sodar study.
Dotted circles are at increments of 5% beginning with 0% at the center.

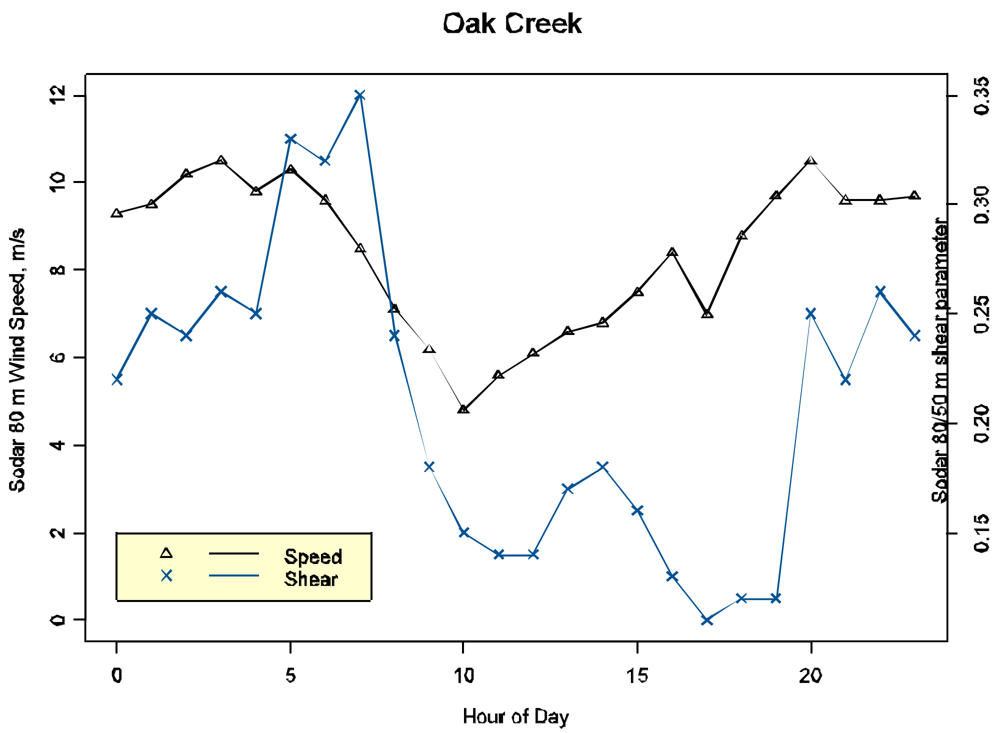


Figure 25: Oak Creek sodar 80 m speed and 80/50 m shear, by hour of day.

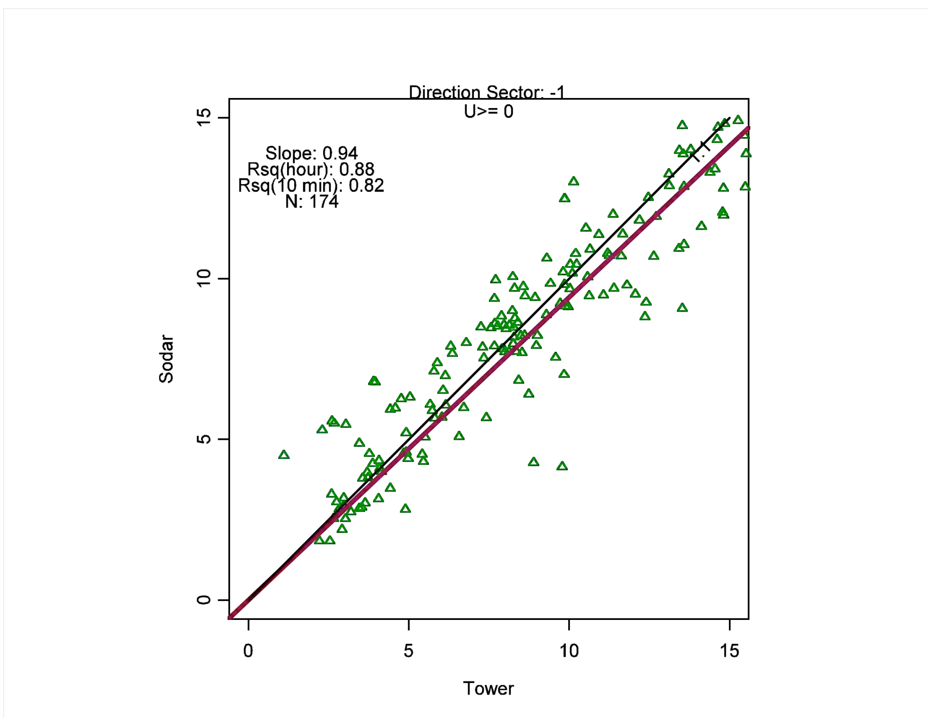


Figure 26: Hourly averaged sodar and tower wind speeds at 70 m for the Oak Creek sodar study.
The slope shown is for the line forced through zero.

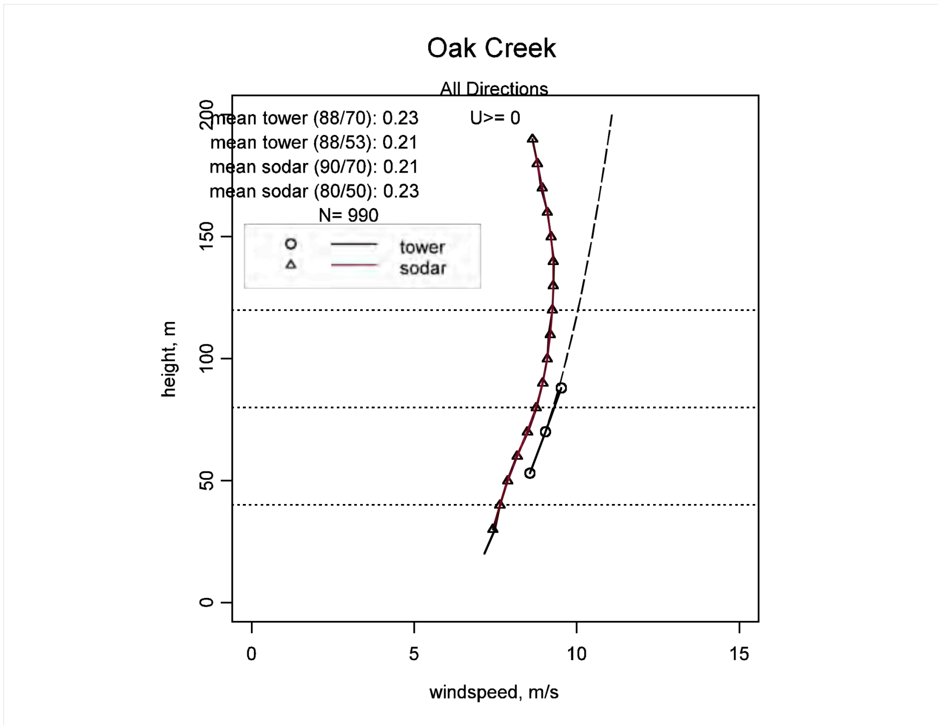


Figure 27: Average wind speed profiles for the Oak Creek sodar and tower, for the Oak Creek sodar study

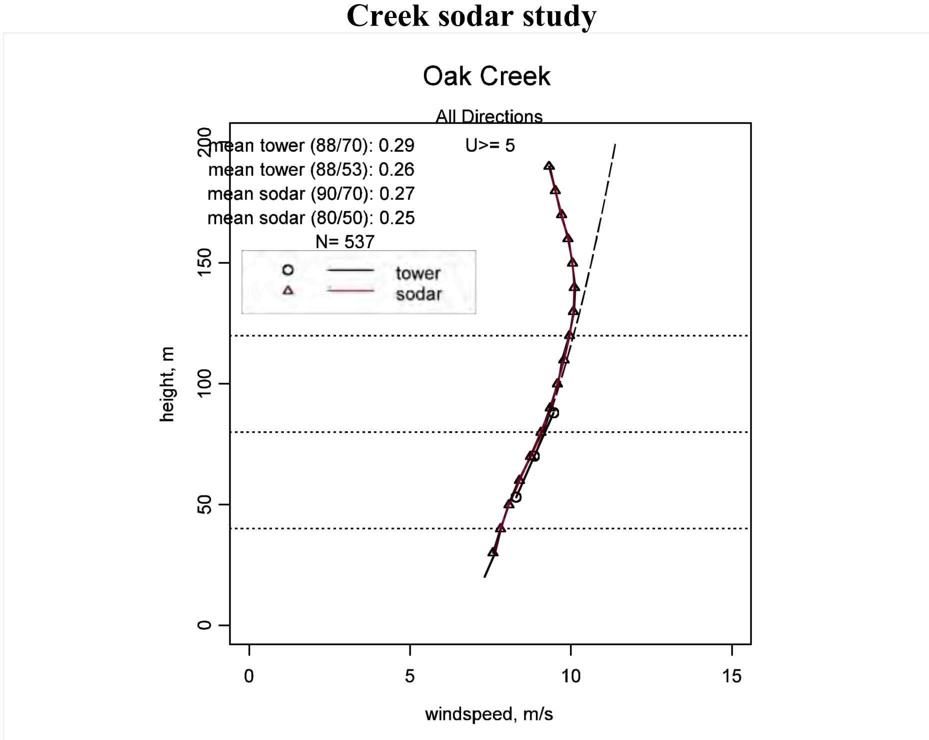


Figure 28: Average wind speed profiles for the Oak Creek sodar and tower for all directions, for 50 m sodar speeds ≥ 5 m/s, excluding the high wind speed event of days 177-179

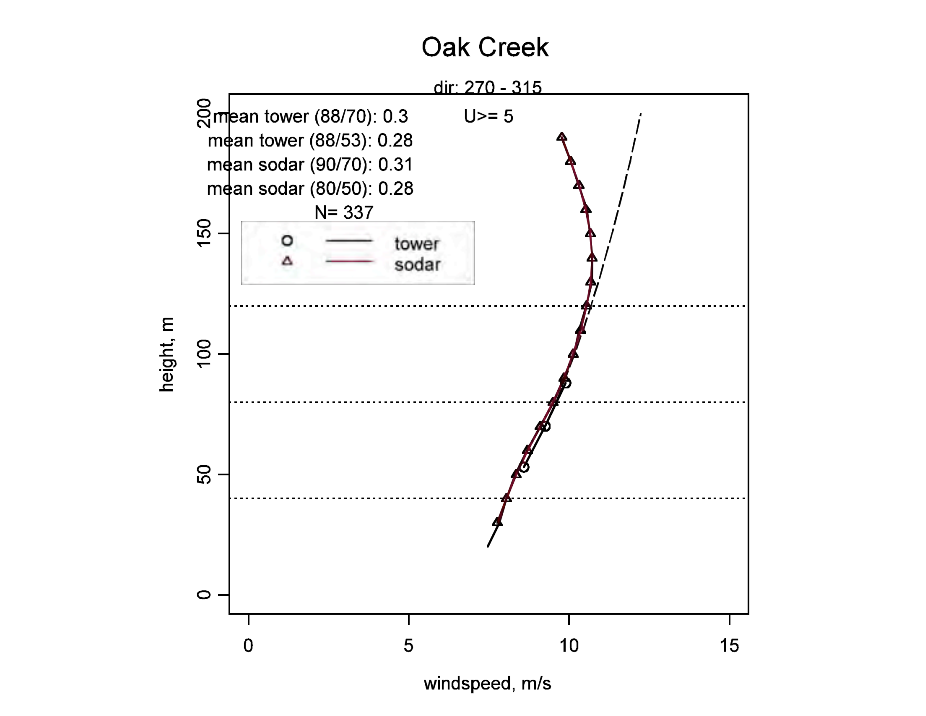


Figure 29: Average wind speed profiles at the Oak Creek tower and sodar, for WNW 50 m sodar speeds ≥ 5 m/s, excluding the high wind speed event of days 177-179

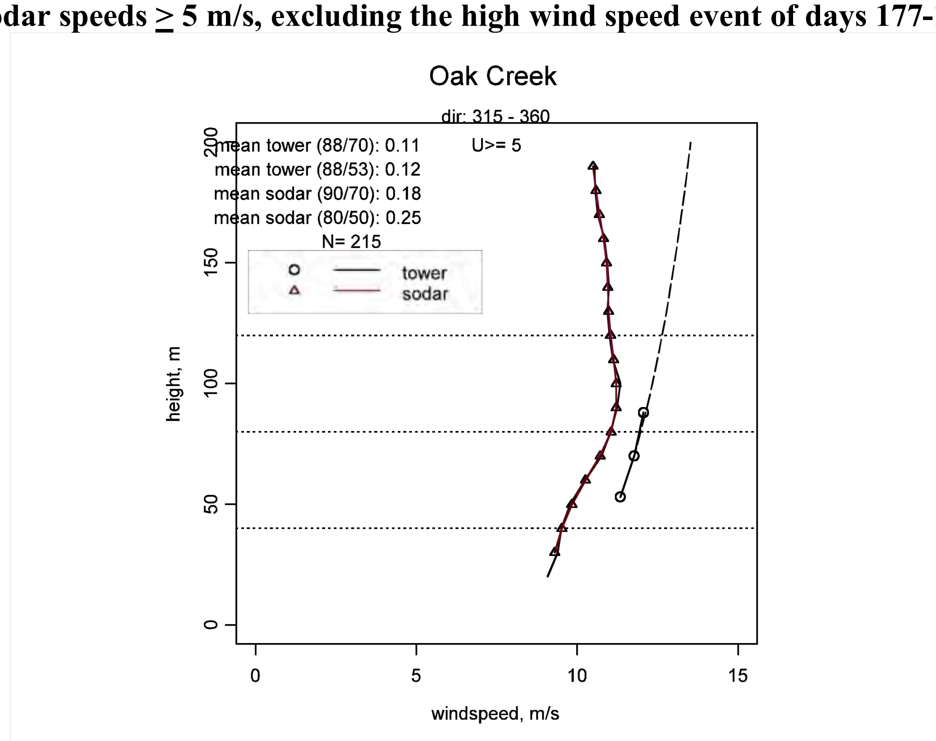


Figure 30: Average wind speed profiles for the Oak Creek tower and sodar, for NNW 50 m sodar speeds > 5 m/s, excluding the high wind speed event of days 177-179

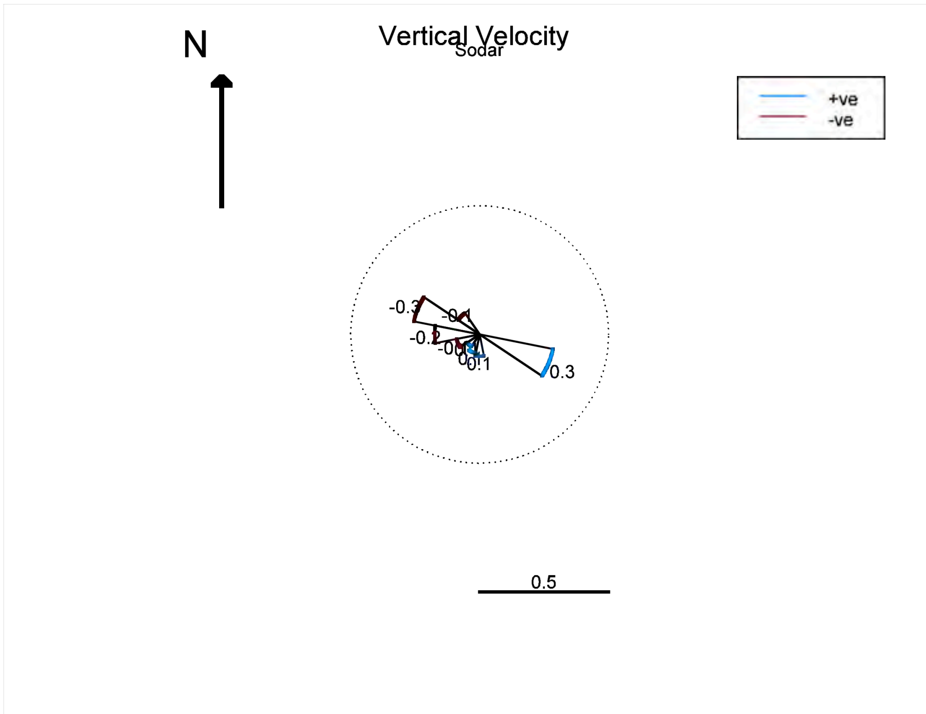


Figure 31: Oak Creek sodar vertical velocity, at 50 m (positive upward)

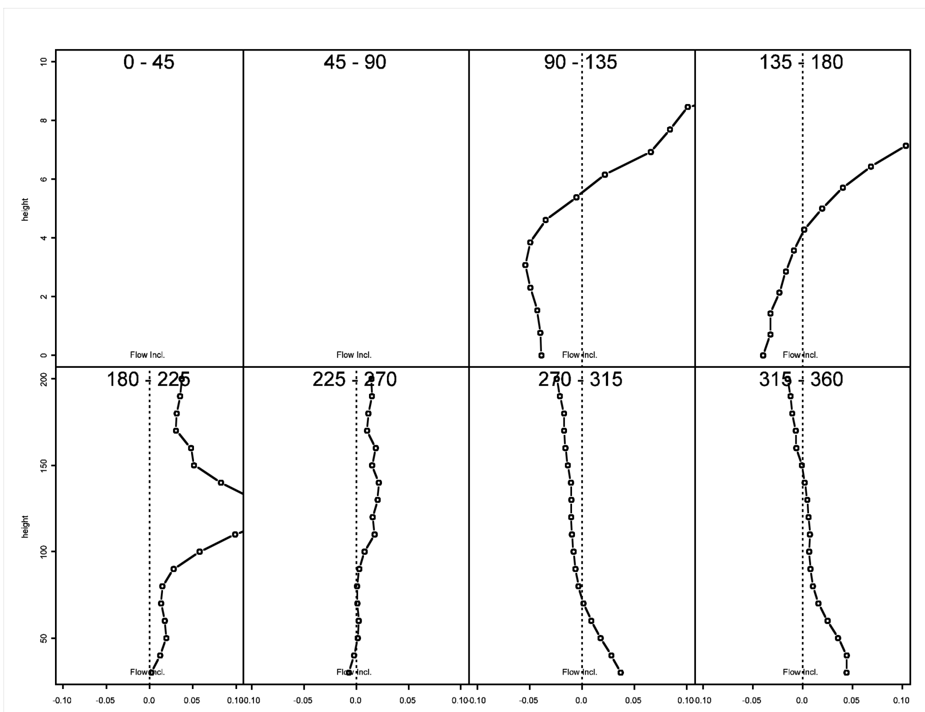


Figure 32: Profiles of Oak Creek flow inclination by wind direction sector. All data periods are included.

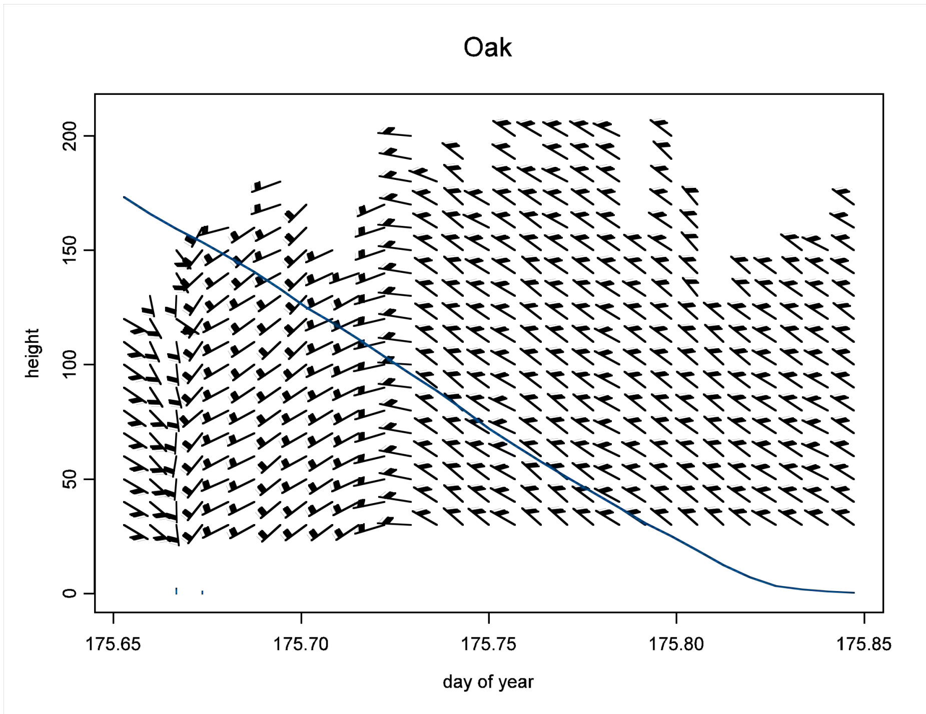


Figure 33: Time-height section of the Oak Creek sodar wind profile during the shift in flow regimes from S to NW on day 175.
The blue line indicates the solar radiation.

Table 37: Oak Creek sodar mean speeds ("U") and shear parameters at specified heights (m) by speed (m/s).
Speed bin designations are the lower bound of the bin.

Speed	1	2	3	4	5	6	7
U@30 m	1.7	2.5	3.3	4.4	5.4	6.2	7.0
U@50 m	1.7	2.6	3.5	4.5	5.6	6.5	7.5
U@80 m	2.0	2.7	3.7	4.8	6.2	7.3	8.5
U@110 m	2.2	2.8	3.9	5.2	6.7	8.1	9.5
U@120 m	2.2	2.9	3.9	5.2	6.9	8.4	9.8
U@140 m	2.3	2.9	3.9	5.2	7.2	8.8	10.2
Shear (50/30 m)	0.10	0.09	0.11	0.06	0.07	0.08	0.13
Shear (80/50 m)	0.33	0.10	0.16	0.14	0.22	0.24	0.27
Shear (110/80 m)	0.20	0.13	0.15	0.23	0.26	0.34	0.36
Number of Profiles @ 50 m	18	54	81	83	91	124	147
Speed	8	9	10	11	12	13	14
U@30 m	7.8	9.2	10.0	10.9	11.7	12.3	13.4
U@50 m	8.4	9.5	10.5	11.5	12.4	13.4	14.4
U@80 m	9.5	10.6	11.6	12.6	13.8	14.8	16.2
U@110 m	10.3	11.1	12.2	13.4	14.8	15.9	18.0
U@120 m	10.5	11.1	12.3	13.4	14.9	16.0	18.4
U@140 m	10.8	11.2	12.2	13.4	14.8	14.9	
Shear (50/30 m)	0.15	0.07	0.09	0.10	0.12	0.16	0.14
Shear (80/50 m)	0.25	0.22	0.21	0.19	0.22	0.22	0.25
Shear (110/80 m)	0.26	0.16	0.17	0.19	0.21	0.22	0.34
Number of Profiles @ 50 m	95	59	51	85	61	49	11

Table 38: Locations and types of sensors on the Geyserville tower.
At each height sensors were mounted on booms oriented to 325^o (primary) and 145^o (secondary).

Instrument	Geyserville Tower Height, m
NRG Max 40 cup	60
NRG Max 40 cup	44
NRG-Max 40 cup	29
NRG-200 P Vane	58
NRG-200 P Vane	43
NRG-200 P Vane	28
RMYoung Temperature	5
Licor Pyranometer	1.5


Figure 34: Geyserville tower site

Figure 35: Map showing locations of Mayacamas sodar and tower sites

Figure 36: Mayacamas sodar site, looking east

Figure 37: Mayacamas sodar site, looking south

Figure 38: Calpine sodar site, looking east

Figure 39: Calpine sodar site, looking south

Figure 40: Calpine sodar site, looking west

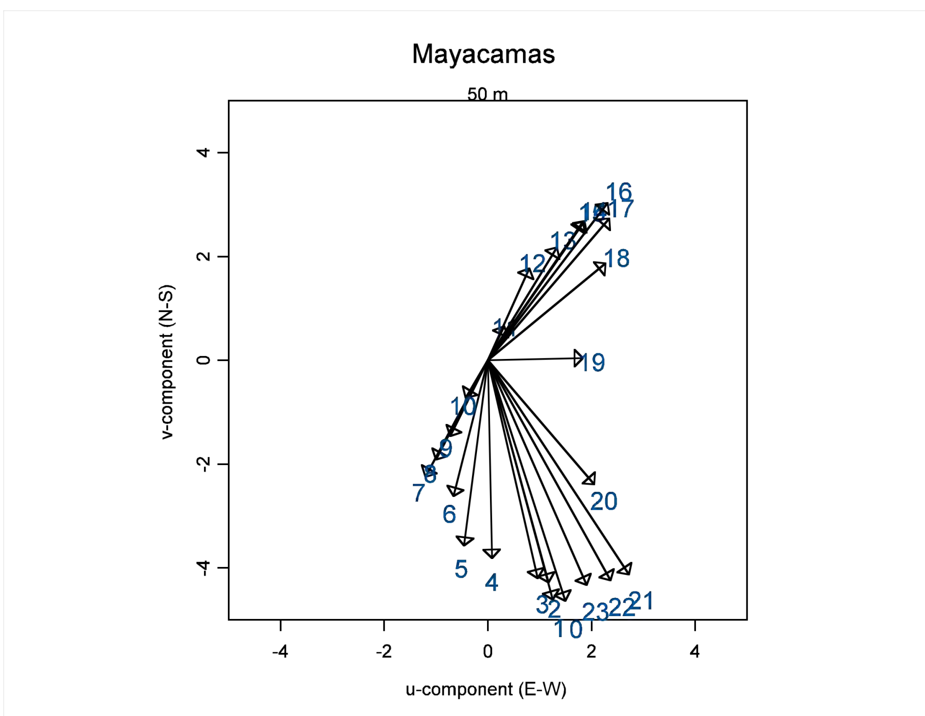


Figure 41: Mayacamas sodar hodograph, at 50 m.
Arrows depict the wind vector for each labeled hour.

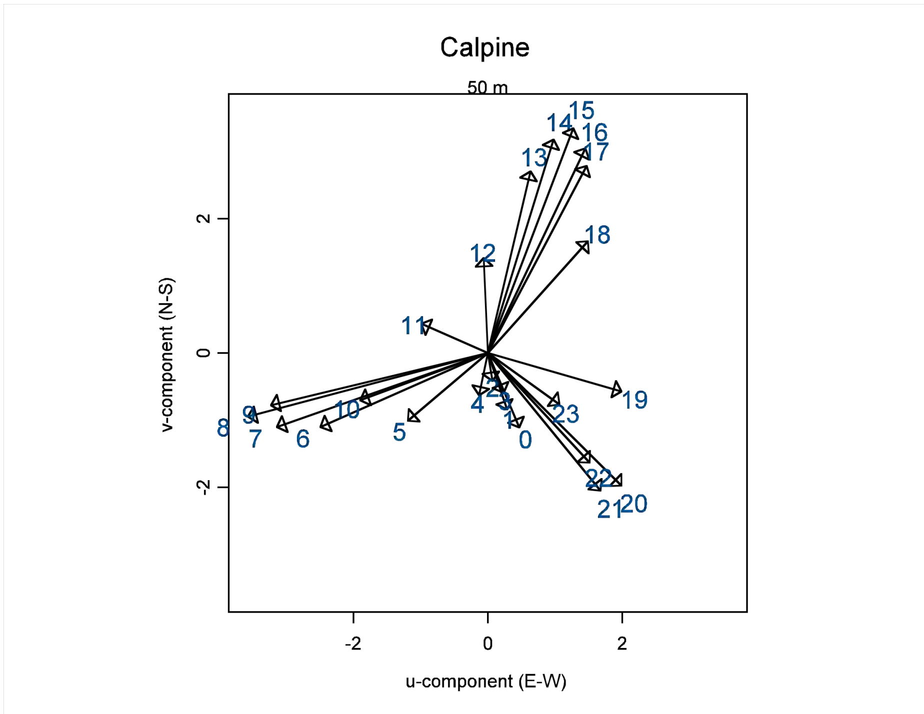


Figure 42: Calpine sodar hodograph, at 50 m.
Arrows depict the wind vector for each labeled hour.

Table 39: Mayacamas sodar and Geyserville tower mean speeds ("U", m/s) and shear parameters for designated 50 m sodar speed intervals, during the Mayacamas sodar study.

Speed	0	1	2	3	4	5	6	7
Sodar U@30 m	0.5	1.4	2.5	3.5	4.4	5.4	6.4	7.3
Sodar U@40 m	0.6	1.4	2.5	3.5	4.4	5.4	6.4	7.4
Sodar U@60 m	0.9	1.6	2.5	3.4	4.4	5.5	6.5	7.8
Sodar U@80 m	1.7	2.2	2.7	3.5	4.7	6.0	6.8	8.2
Sodar U@110 m	2.2	2.7	3.2	3.7	5.0	6.6	7.3	8.7
Sodar shear (60/40 m)	1.19	0.27	-0.04	-0.06	0.01	0.05	0.04	0.11
Sodar shear (80/60 m)	2.27	1.12	0.28	0.13	0.19	0.30	0.19	0.21
Sodar Number of Profiles	217	362	481	498	386	251	211	138
Tower U@29 m	2.6	3.3	3.5	4.5	5.6	7.0	7.9	9.5
Tower U@40 m	2.7	3.4	3.7	4.7	5.8	7.0	7.8	9.2
Tower U@60 m	2.6	3.2	3.6	4.6	5.7	6.8	7.6	9.0
Tower U@80 m	2.6	3.4	3.5	4.4	5.6	7.1	8.0	9.7
Tower U@110 m	2.6	3.4	3.4	4.4	5.5	7.2	8.2	9.9
Tower shear (60/29 m)	0.01	0.06	-0.03	-0.03	-0.02	0.05	0.05	0.07
Tower shear (60/44 m)	-0.12	-0.03	-0.17	-0.13	-0.11	0.03	0.06	0.09
Tower Number of Profiles	217	362	481	498	386	251	211	138

Speed	8	9	10	11	12
Sodar U@30 m	8.4	9.2	10.2	11.4	12.1
Sodar	8.5	9.5	10.5	11.7	12.5

U@40 m					
Sodar U@60 m	8.8	10.1	11.0	12.4	13.2
Sodar U@80 m	9.2	10.6	11.3	12.9	13.6
Sodar U@110 m	9.6	11.0	11.6	13.4	14.1
Sodar shear (60/40 m)	0.09	0.15	0.12	0.14	0.13
Sodar shear (80/60 m)	0.17	0.18	0.09	0.15	0.10
Sodar Number of Profiles	120	83	46	25	21
Tower U@29 m	10.4	11.9	12.2	13.5	13.2
Tower U@40 m	10.0	11.5	11.8	13.1	12.9
Tower U@60 m	9.8	11.2	11.6	12.9	12.7
Tower U@80 m	10.6	12.2	12.4	13.7	13.5
Tower U@110 m	10.8	12.5	12.7	14.0	13.7
Tower shear (60/29 m)	0.07	0.08	0.07	0.06	0.06
Tower shear (60/44 m)	0.10	0.11	0.09	0.09	0.09
Tower Number of Profiles	120	83	46	25	21

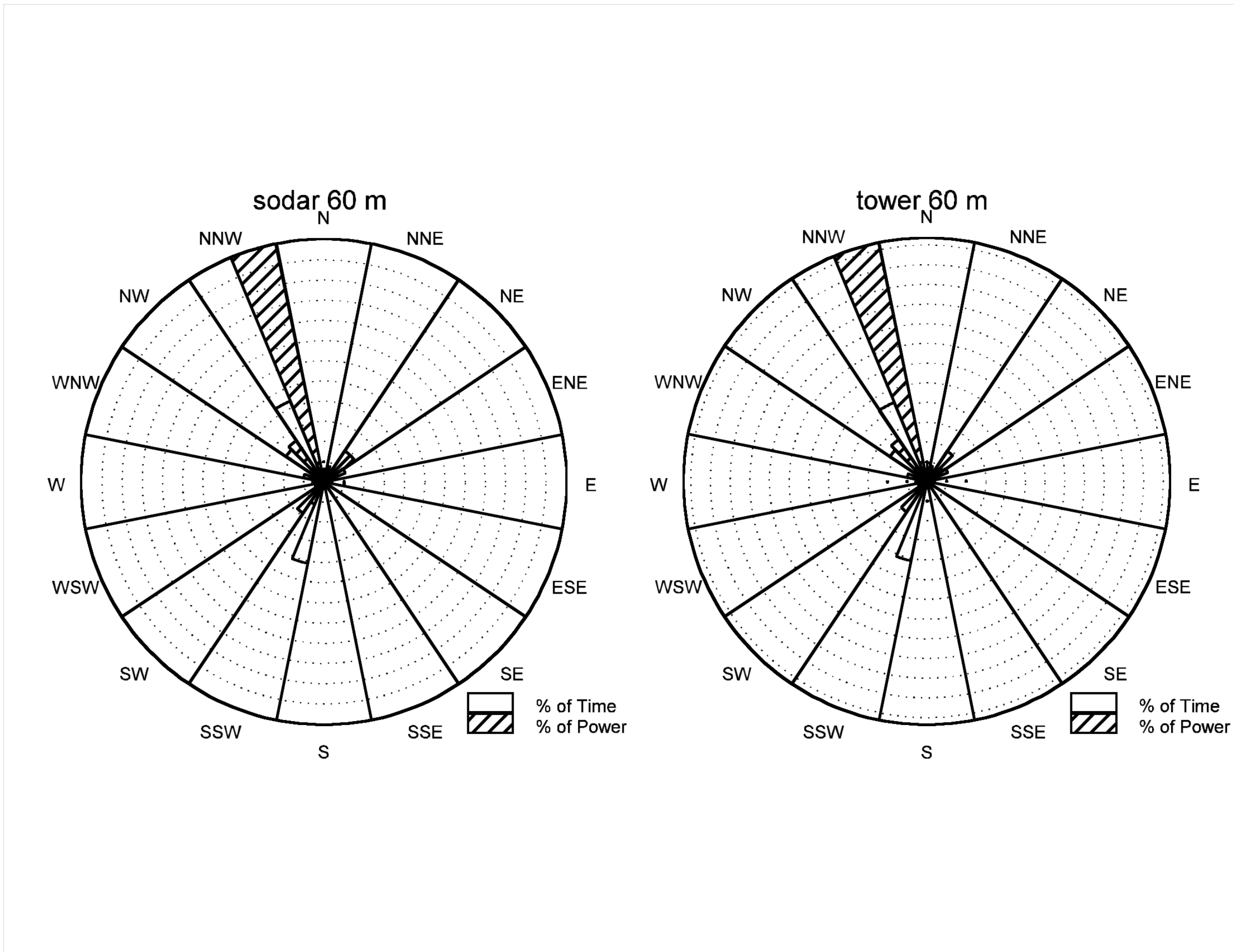


Figure 43: Wind roses for Mayacamas sodar and Geyserville tower during the Mayacamas sodar study.
Dotted circles are at increments of 5% beginning with 0% at the center.

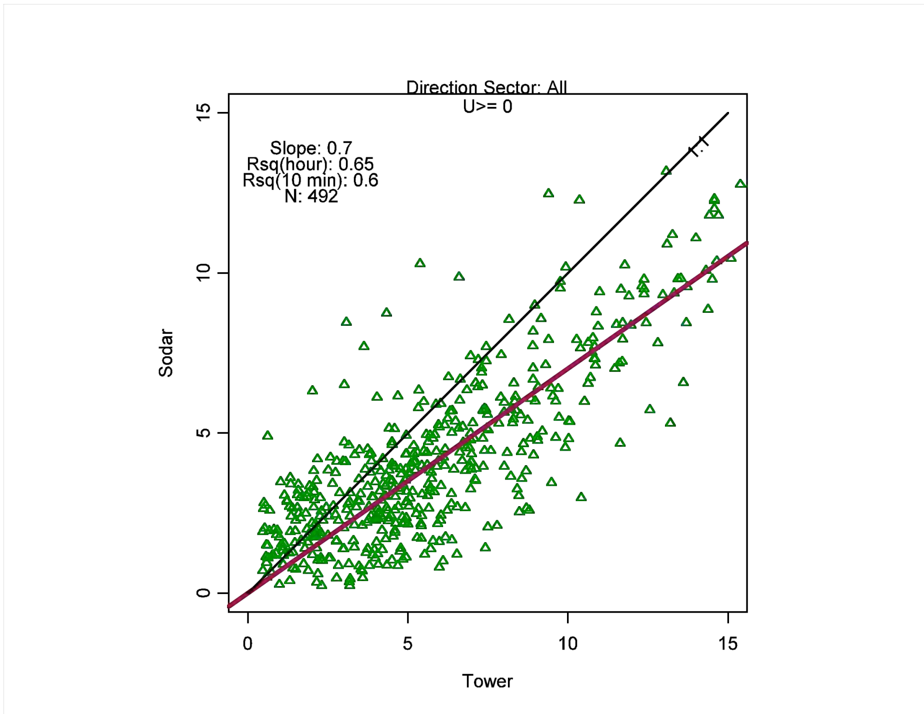


Figure 44: Hourly average wind speeds for the Mayacamas sodar and Geyserville tower at 60 m, for all speeds and directions.
The slope is for the line forced through zero.

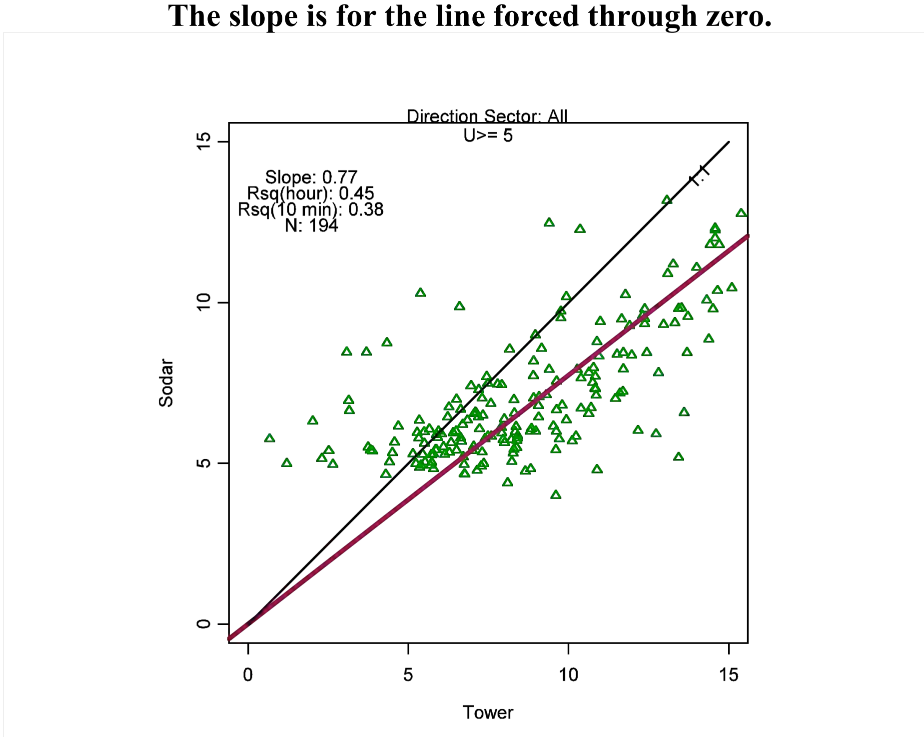


Figure 45: Hourly average wind speeds for the Mayacamas sodar and Geyserville tower at 60 m, for all directions, and 50 m sodar speeds ≥ 5 m/s.
The slope is for the line forced through zero.

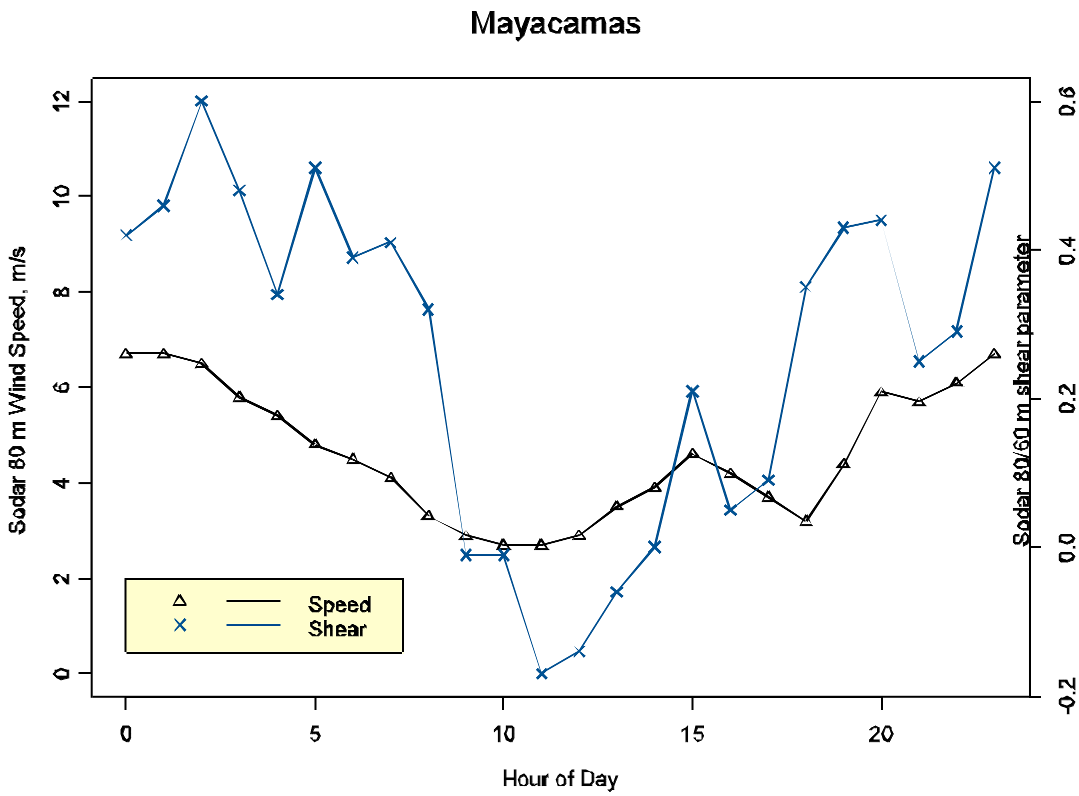


Figure 46: Mayacamas sodar 80 m speed and 80/50 m shear, by hour of day.

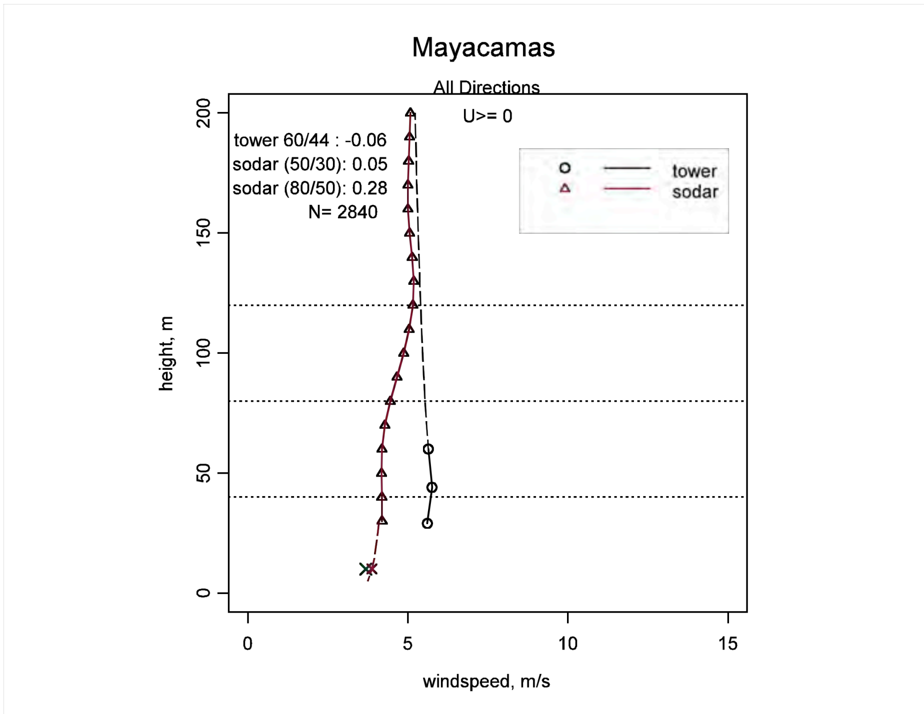


Figure 47: Average wind speed profiles for the Mayacamas sodar and the Geyserville tower, for all speeds and directions.
The dashed line is the extrapolated tower wind profile using the 60/44 m shear parameter. The blue "X" is the mean speed at the Calpine Unit 17 meteorological station, and the red triangle is the extrapolated sodar speed to 10 m, using the sodar 50/30 m shear parameter.

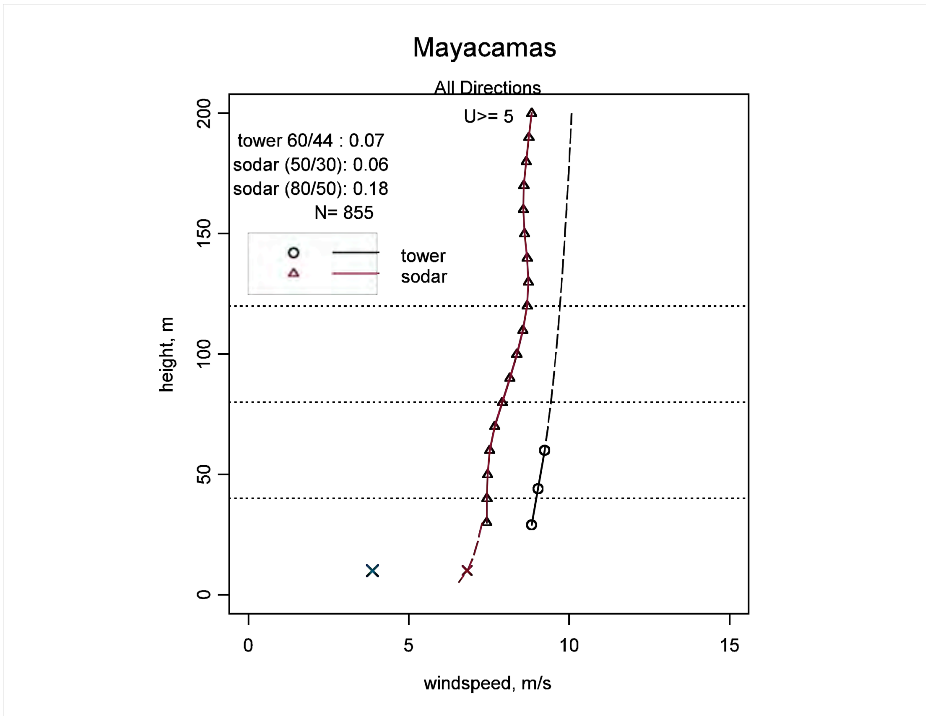


Figure 48: Average wind speed profiles for the Mayacamas sodar and the Geyserville tower, for all directions, and 50 m sodar speeds ≥ 5 m/s.
The dashed line is the extrapolated tower wind profile using the 60/44 m shear parameter. The blue "X" is the mean speed at the Calpine Unit 17 meteorological station, and the red triangle is the extrapolated sodar speed to 10 m, using the sodar 50/30 m shear parameter.

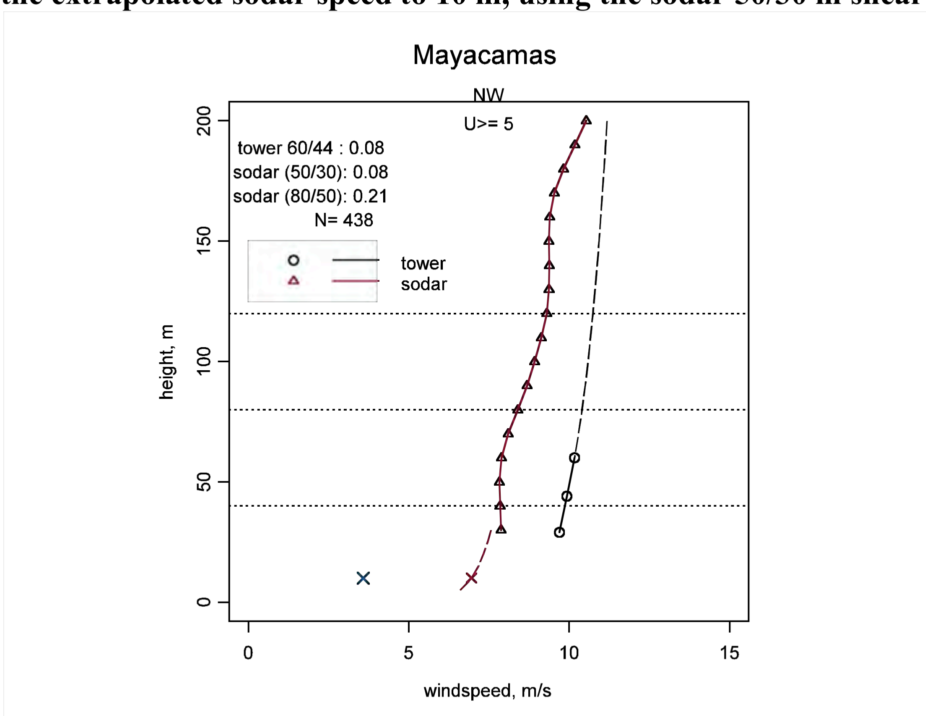


Figure 49: Average wind speed profiles for the Mayacamas sodar and the Geyserville tower, for 50 m sodar speeds ≥ 5 m/s, and wind from the NW

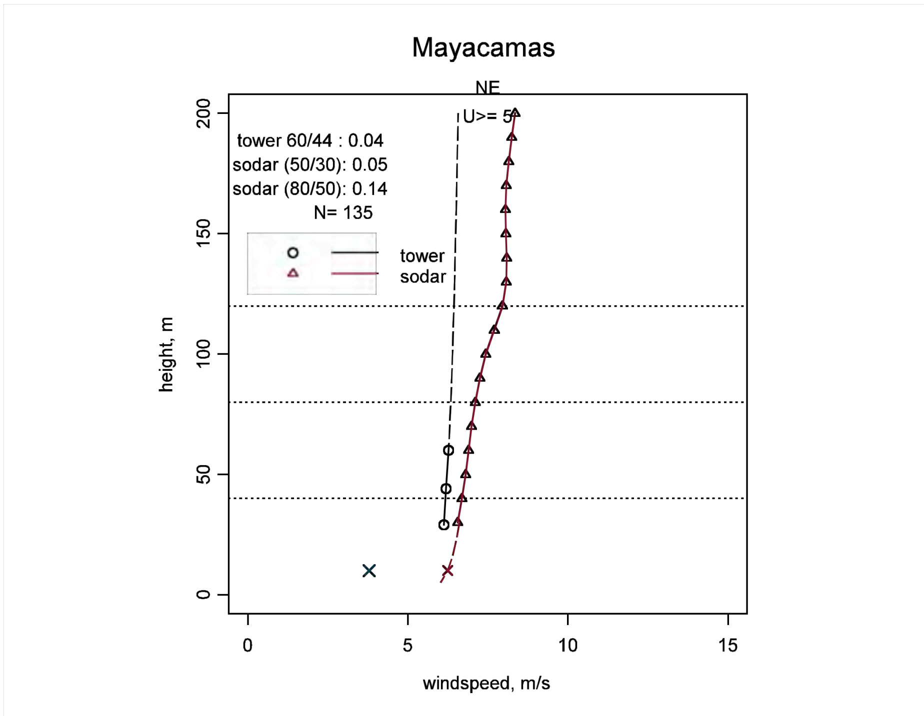


Figure 50: Average wind speed profiles for the Mayacamas sodar and the Geyserville tower, for 50 m sodar speeds ≥ 5 m/s, and wind from the NE

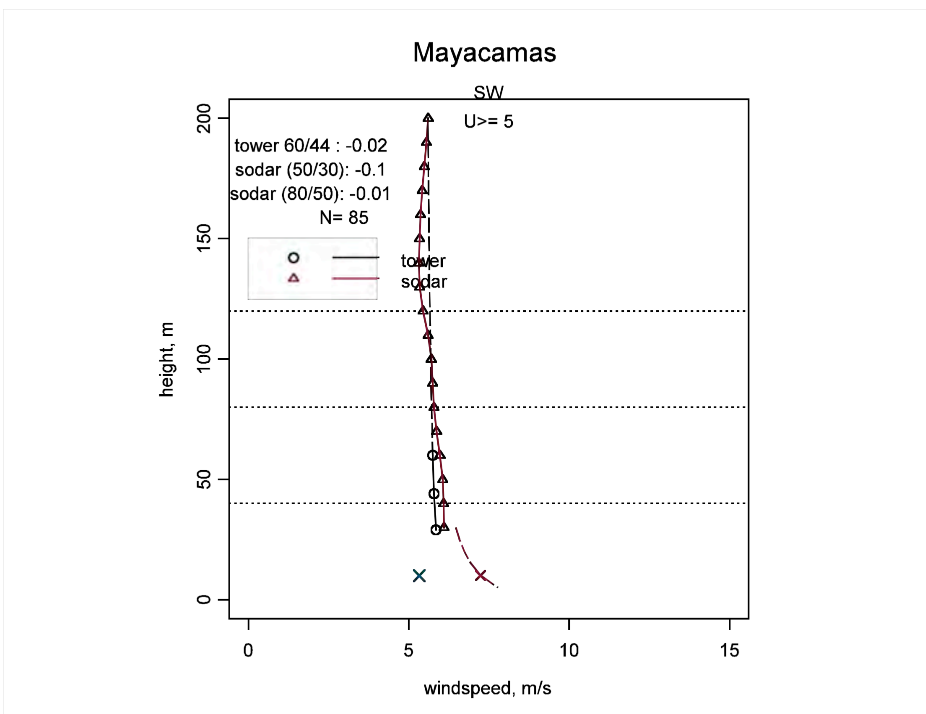


Figure 51: Average wind speed profiles for the Mayacamas sodar and the Geyserville tower, for 50 m sodar speeds ≥ 5 m/s, and wind from the SW

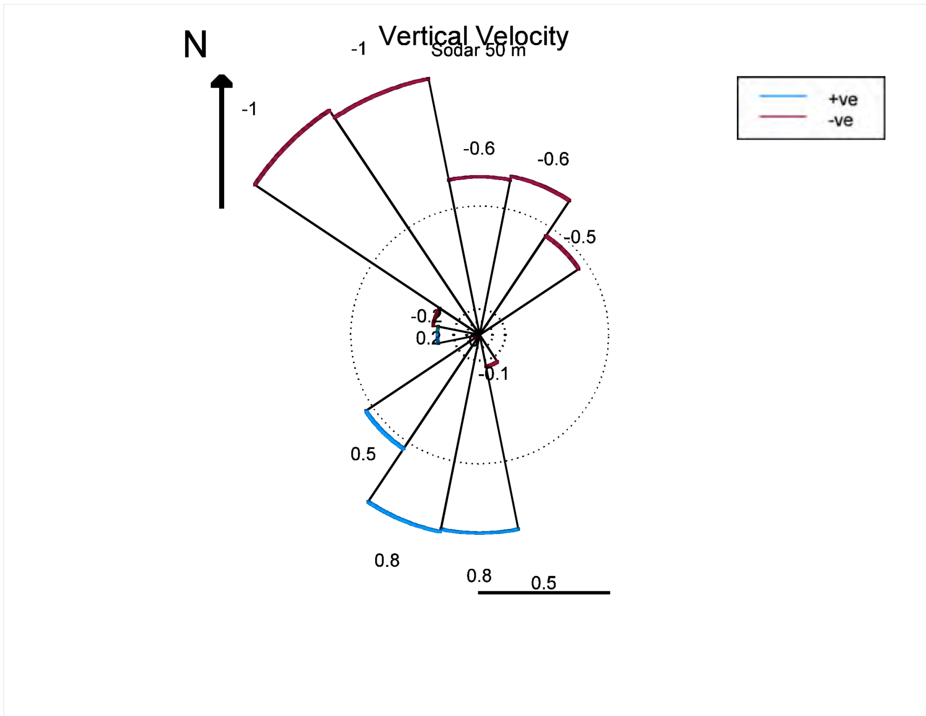


Figure 52: Mayacamas sodar vertical velocity, 50 m (positive upward)

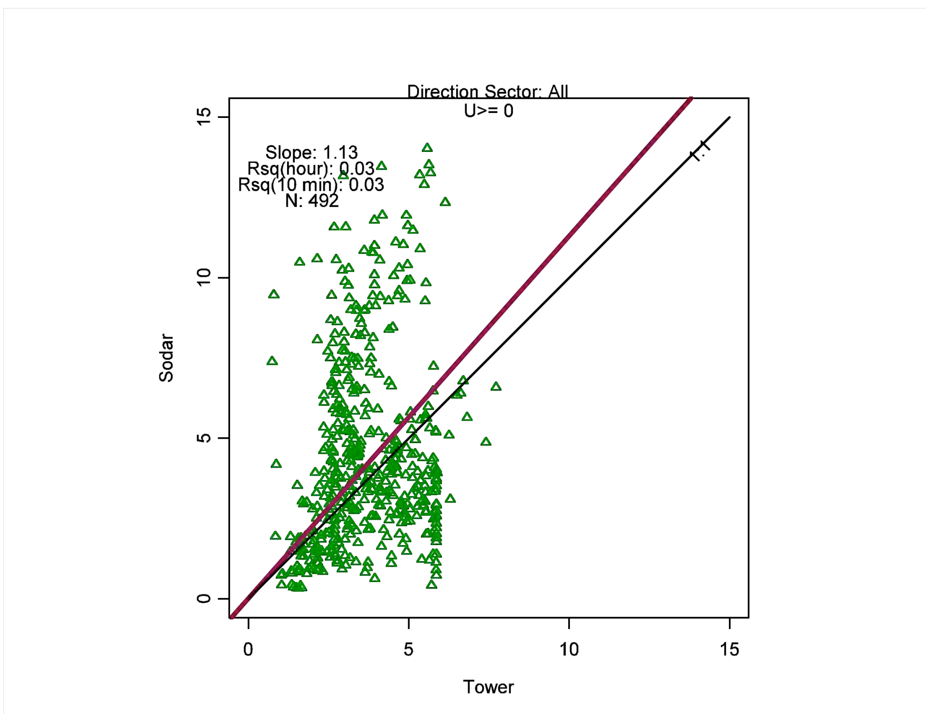


Figure 53: Scatter plot of Mayacamas sodar 80 m wind speeds compared to Calpine Unit 17 met stations wind speeds, during the Mayacamas sodar study

Table 40: Calpine sodar and Geyserville tower mean speed (“U”, m/s) and shear parameters for designated 50 m sodar speed intervals, during the Calpine sodar study period

Speed	0	1	2	3	4	5	6	7	8
Sodar U@30 m	0.6	1.5	2.5	3.5	4.3	5.4	6.6	7.3	8.3
Sodar U@40 m	0.5	1.5	2.5	3.5	4.3	5.5	6.7	7.5	8.5
Sodar U@60 m	0.6	1.4	2.4	3.5	4.3	5.5	6.9	7.8	8.9
Sodar U@80 m	1.1	1.9	2.6	3.6	4.4	5.5	7.2	8.1	9.3
Sodar U@110 m	2.5	3.2	3.1	3.9	4.6	5.8	7.8	8.6	10.0
Sodar shear (60/40 m)	0.04	-0.11	-0.02	0.01	0.00	0.01	0.07	0.10	0.12
Sodar shear (80/60 m)	2.28	1.01	0.29	0.14	0.02	0.04	0.11	0.15	0.15
Sodar Number of Profiles	147	278	298	229	146	53	12	9	10
Tower U@29 m	3.3	3.9	3.8	3.9	4.0	3.9	4.6	5.6	4.2
Tower U@40 m	3.6	4.1	4.1	4.0	4.1	4.0	4.7	5.6	4.3
Tower U@60 m	3.5	4.1	4.0	4.0	4.1	3.9	4.6	5.7	4.4
Tower U@80 m	3.2	3.9	3.8	3.9	4.0	3.9	4.6	5.6	4.1
Tower U@110 m	3.1	3.8	3.7	3.8	3.9	4.0	4.6	5.5	4.0
Tower shear (60/29 m)	-0.09	-0.04	-0.06	-0.03	-0.04	0.02	0.00	-0.02	-0.06
Tower shear (60/44 m)	-0.24	-0.15	-0.20	-0.13	-0.11	-0.07	-0.05	-0.02	-0.10

Tower Number of Profiles	147	278	298	229	146	53	12	9	10

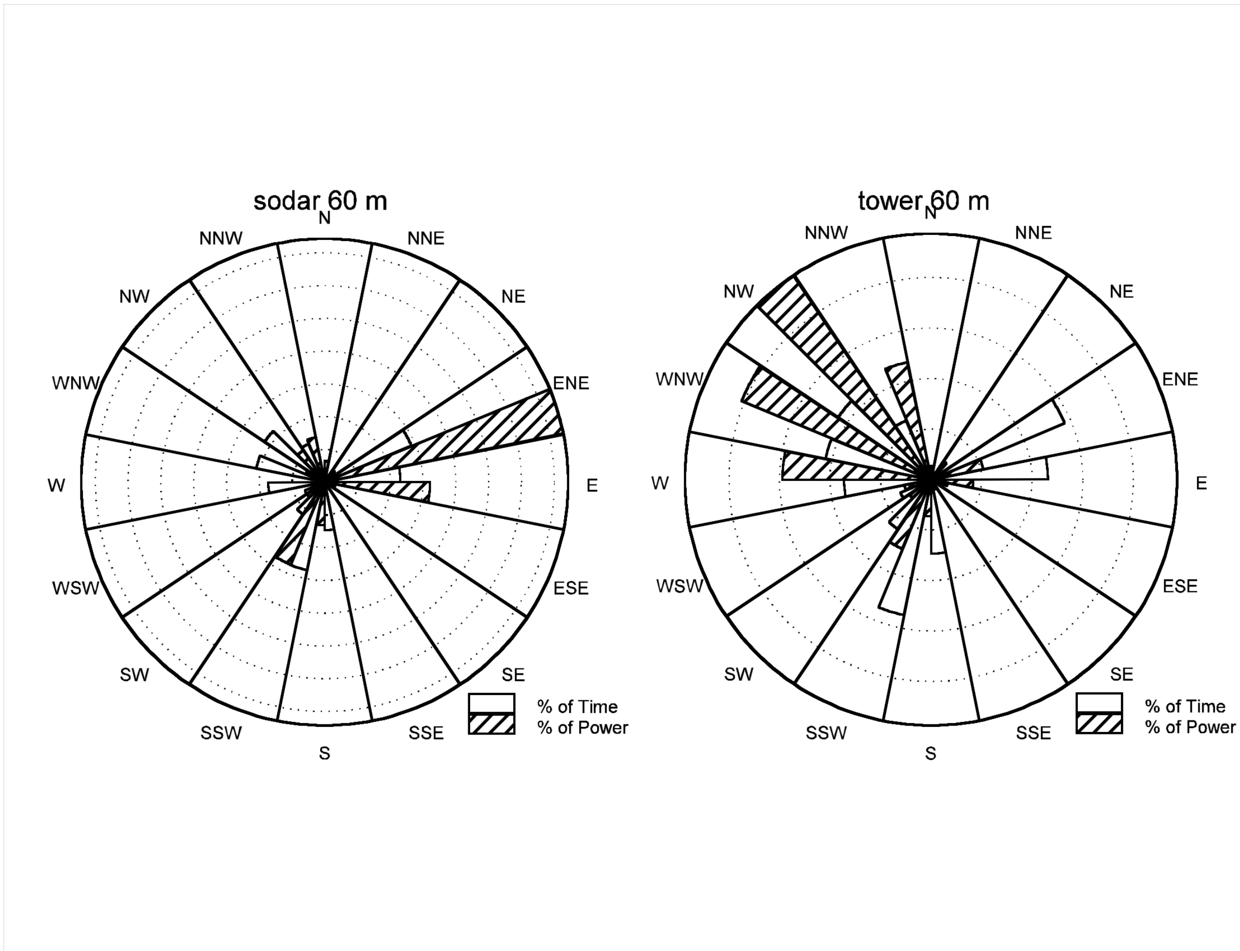


Figure 54: Wind roses for Calpine sodar site and Geyserville tower during the Calpine sodar study.
Dotted circles are at increments of 5% beginning with 0% at the center.

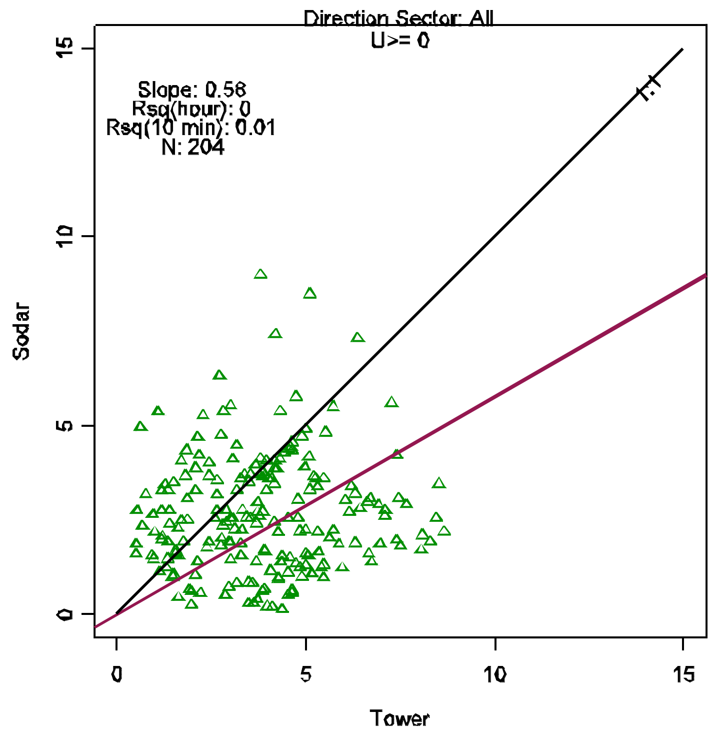


Figure 55: Hourly averaged Calpine sodar and Geyserville tower wind speeds at 60 m, during the Calpine sodar study.
The slope shown is for the line forced through zero.

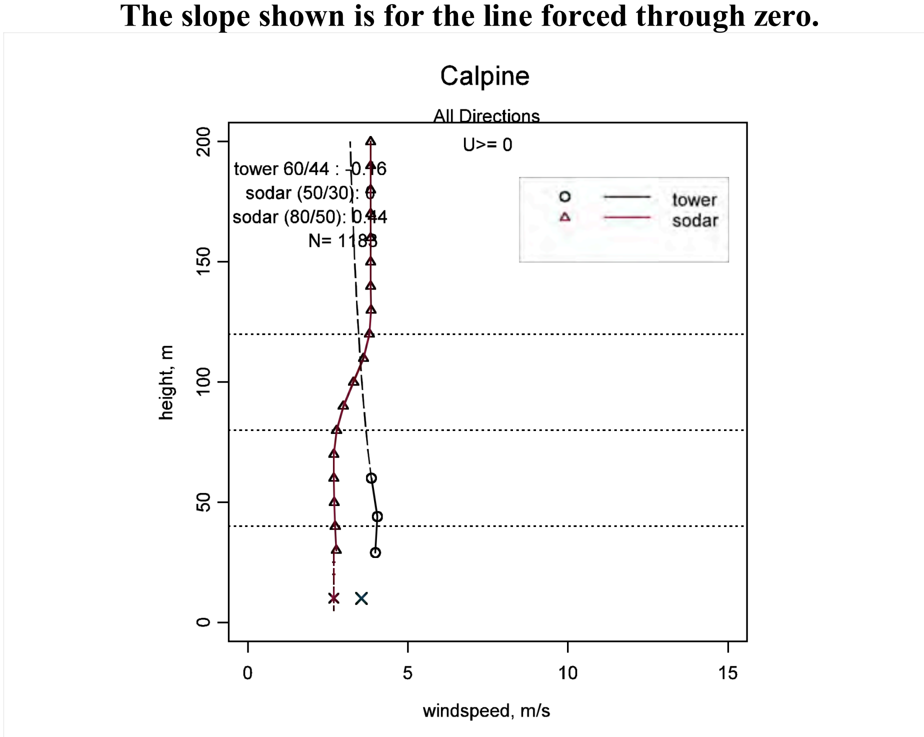


Figure 56: Average wind speed profiles for the Calpine sodar and Geyserville tower. The blue "X" represents the wind speed at the Calpine Unit 17 meteorological station, while the red triangle indicates the sodar 10 m speed, extrapolated down using the sodar 50/30 shear. parameter.

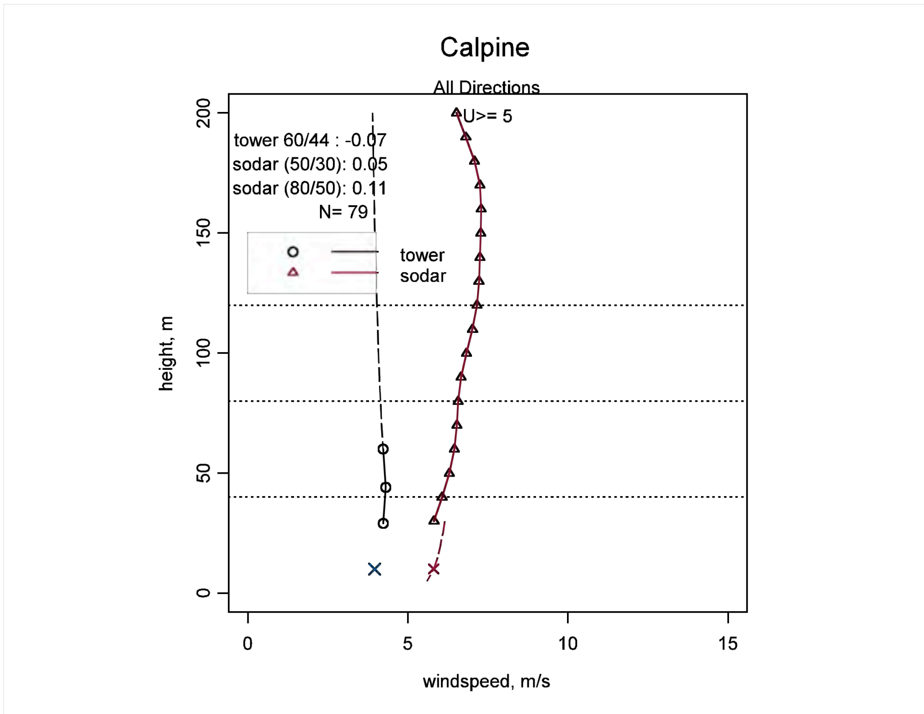


Figure 57: Average Calpine sodar, Geyserville tower, Calpine Unit 17 speed profiles, for 50 m sodar speeds > 5 m/s.
The blue "X" represents the wind speed at the Calpine Unit 17 meteorological station, while the red triangle indicates the sodar 10 m speed, extrapolated down using the sodar 50/30 shear parameter.

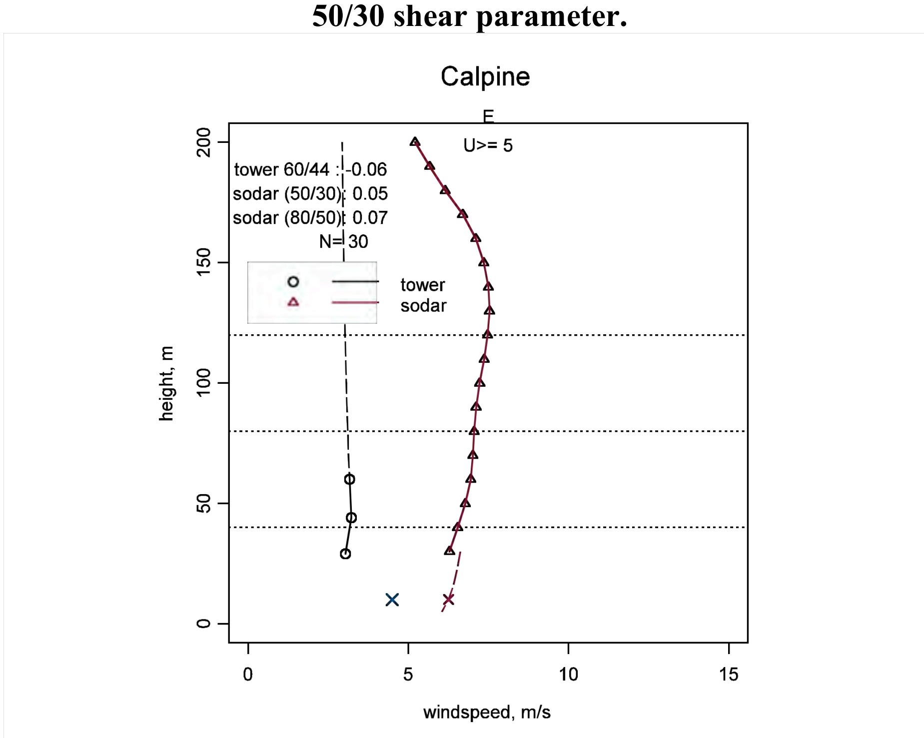


Figure 58: Average Calpine sodar, Geyserville tower, and Calpine Unit 17 wind speed profiles, for 50 m sodar wind speed > 5 m/s, in the E direction sector.

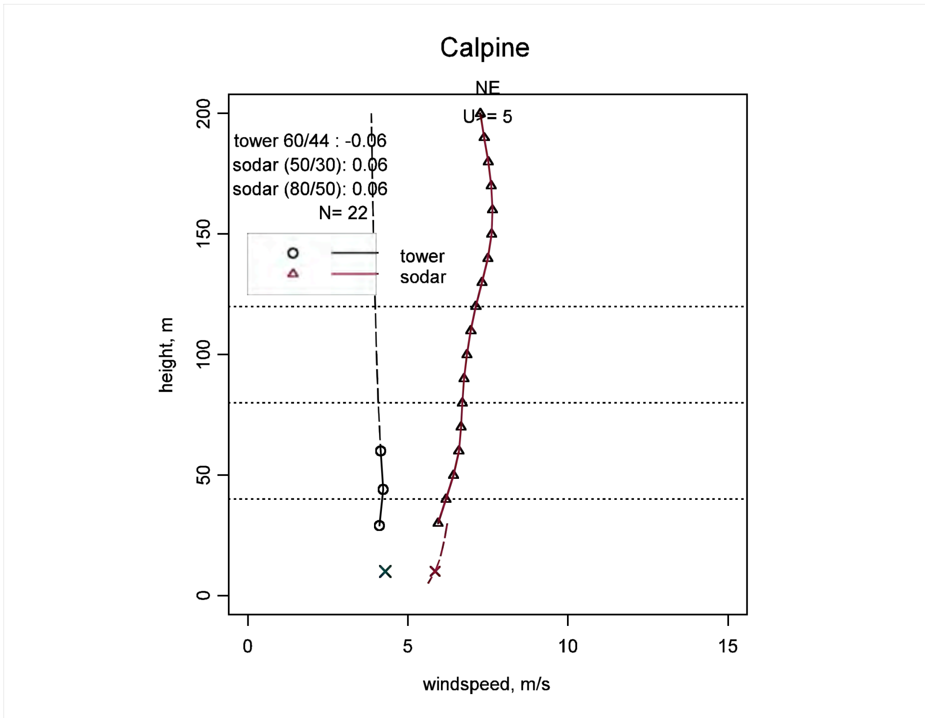


Figure 59: Average Calpine sodar, Geyserville tower, and Calpine Unit 17 wind speed profiles, for 50 m sodar wind speeds > 5 m/s, with NE winds

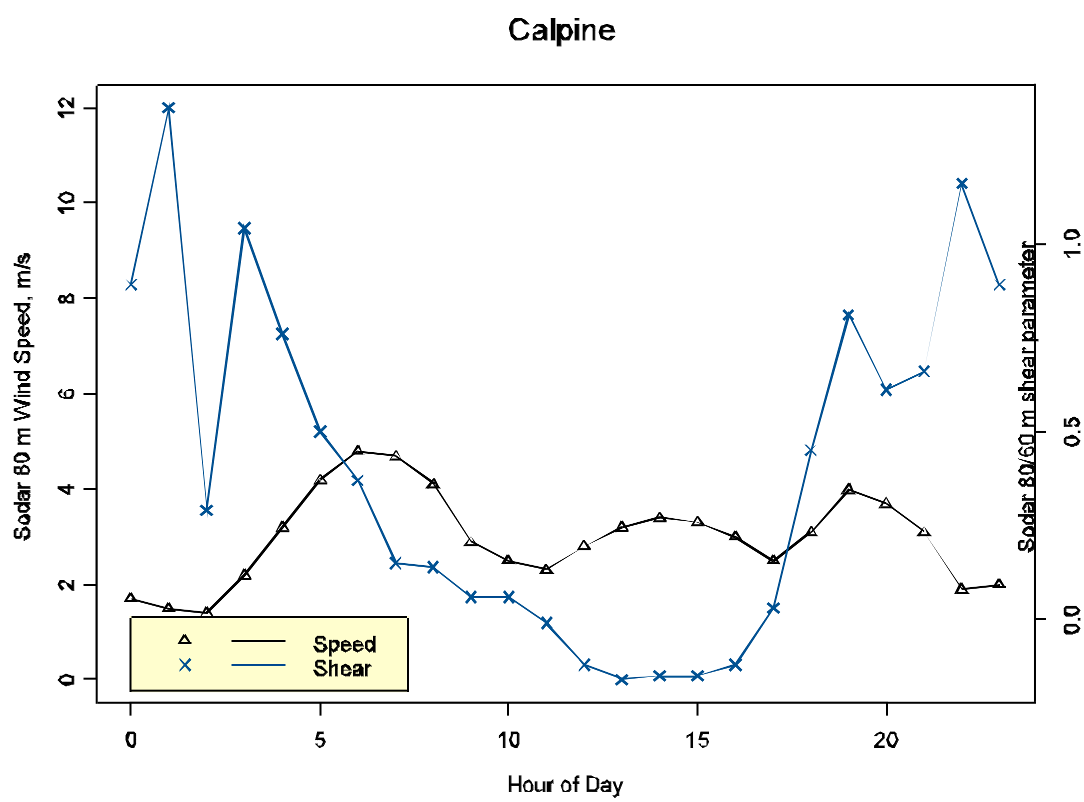


Figure 60: Calpine sodar mean 80 m speed and 80/60 m shear, by hour of day

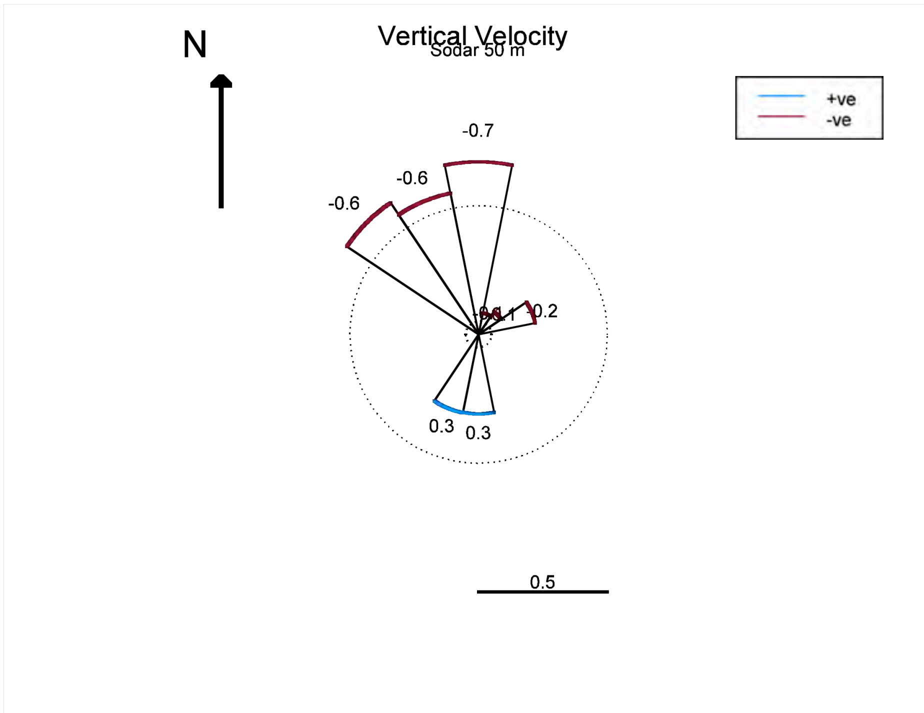


Figure 61: Calpine sodar vertical velocity (positive upward)

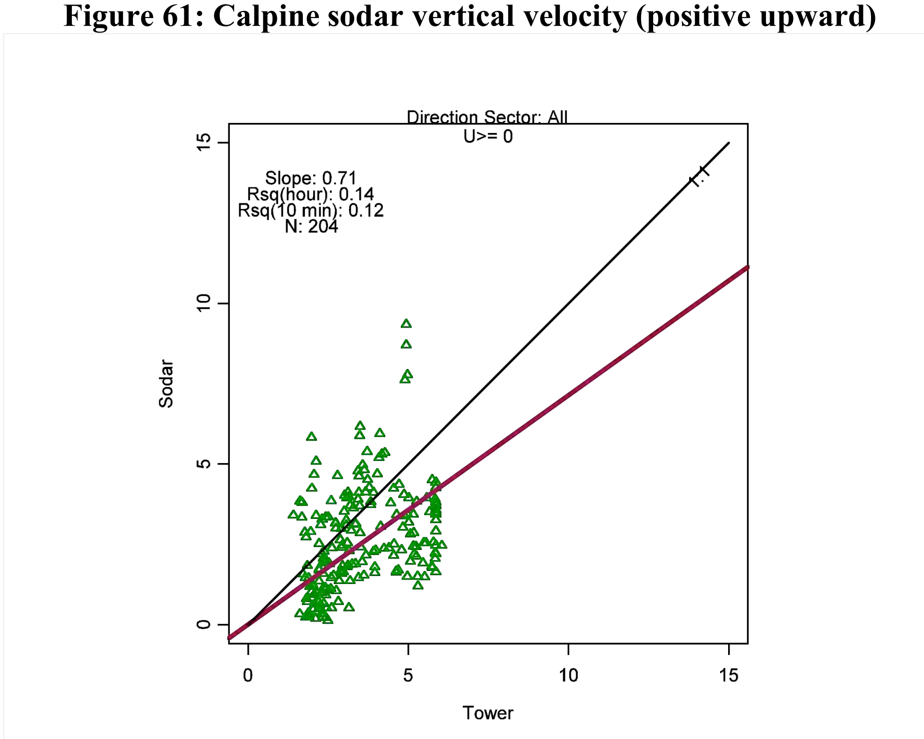


Figure 62: Scatter plot of Calpine sodar 80 m wind speeds with Calpine Unit 17 wind speeds during the Calpine sodar study period

Figure 63: Mojave sodar site, looking west

Figure 64: Mojave sodar site, looking south

Table 41: Mojave mean speeds and shear parameters by 50 m wind speed.
Speed bins are labeled as the lower limit of speed (m/s) for each bin.

Speed	**0**	**1**	**2**	**3**	**4**	**5**	**6**
U@30 m	0.9	1.5	2.4	3.2	4.2	5.1	6.0
U@50 m	0.7	1.5	2.5	3.5	4.5	5.5	6.5
U@80 m	1.1	1.8	2.8	3.9	4.8	5.9	6.8
U@110 m	1.8	2.4	3.2	4.4	5.2	6.5	7.4
U@120 m	1.9	2.5	3.2	4.4	5.2	6.6	7.6
U@140 m	2.2	2.6	3.1	4.2	5.3	6.7	8.0
Shear (50/30 m)	-0.69	-0.01	0.05	0.18	0.13	0.13	0.14
Shear (80/50 m)	1.15	0.39	0.21	0.23	0.15	0.15	0.09
Shear (110/80 m)	1.53	0.94	0.48	0.35	0.25	0.31	0.29
Number of Profiles	248	443	298	211	143	113	103

Speed	**7**	**8**	**9**	**10**	**11**	**12**	**13**
U@30 m	7.1	7.9	8.9	10.0	10.9	11.9	12.9
U@50 m	7.5	8.4	9.5	10.5	11.5	12.5	13.5
U@80 m	7.7	8.9	10.1	11.2	12.1	13.1	14.2
U@110 m	8.4	9.0	10.4	11.5	12.5	13.8	14.7
U@120 m	8.5	9.1	10.5	11.8	12.8	14.0	14.8
U@140 m	8.9	9.5	11.0	12.5	13.3	14.4	14.6
Shear (50/30 m)	0.09	0.14	0.13	0.11	0.10	0.09	0.08
Shear (80/50 m)	0.07	0.11	0.15	0.13	0.10	0.11	0.11
Shear (110/80 m)	0.25	0.03	0.08	0.10	0.11	0.16	0.12
Number of Profiles	66	75	77	120	173	146	141

Speed	**14**	**15**	**16**
U@30 m	13.8	14.8	15.9
U@50 m	14.4	15.4	16.3
U@80 m	15.0	16.0	16.7
U@110 m	15.3	16.1	17.2
U@120 m	15.3	16.1	17.5
U@140 m	15.2	15.9	17.8
Shear (50/30 m)	0.07	0.07	0.05
Shear (80/50 m)	0.09	0.08	0.05
Shear (110/80 m)	0.07	0.03	0.10
Number of	85	56	17

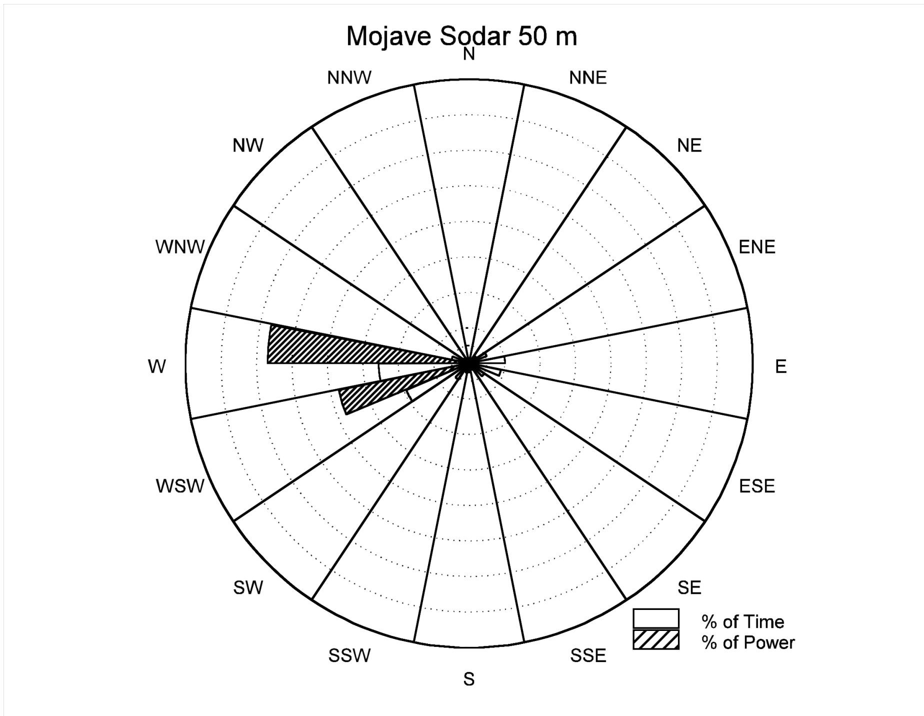


Figure 65: Wind rose for the Mojave sodar.
Dotted circles are at increments of 5% beginning with 0% at the center.

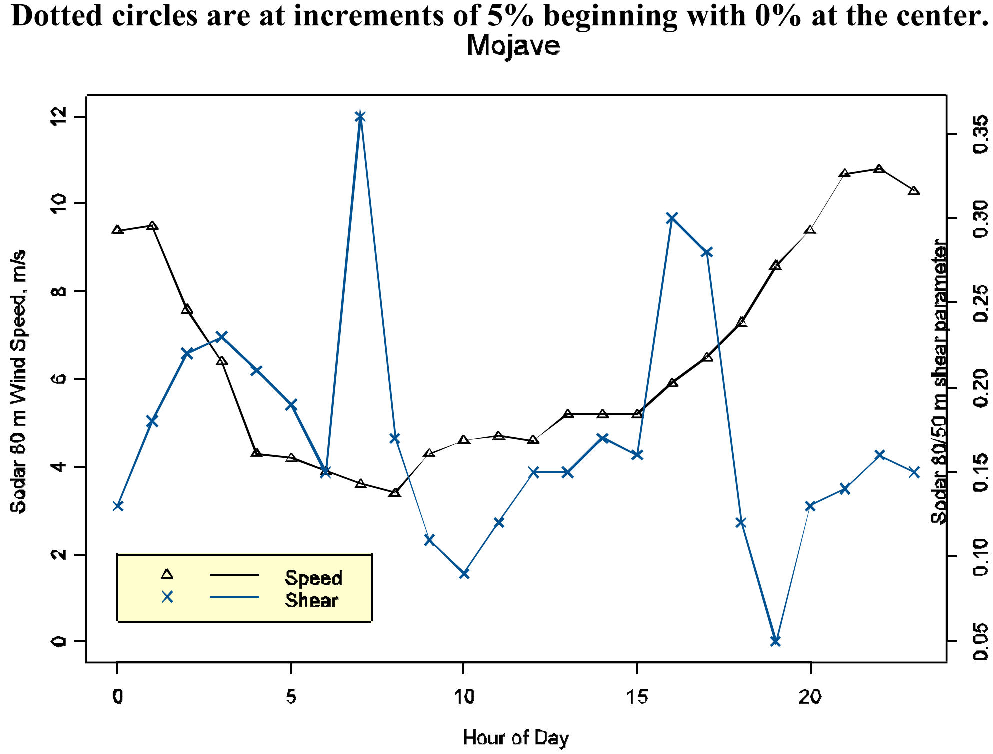


Figure 66: Mojave sodar mean 80 m speed and 80/50 m shear, by hour of day

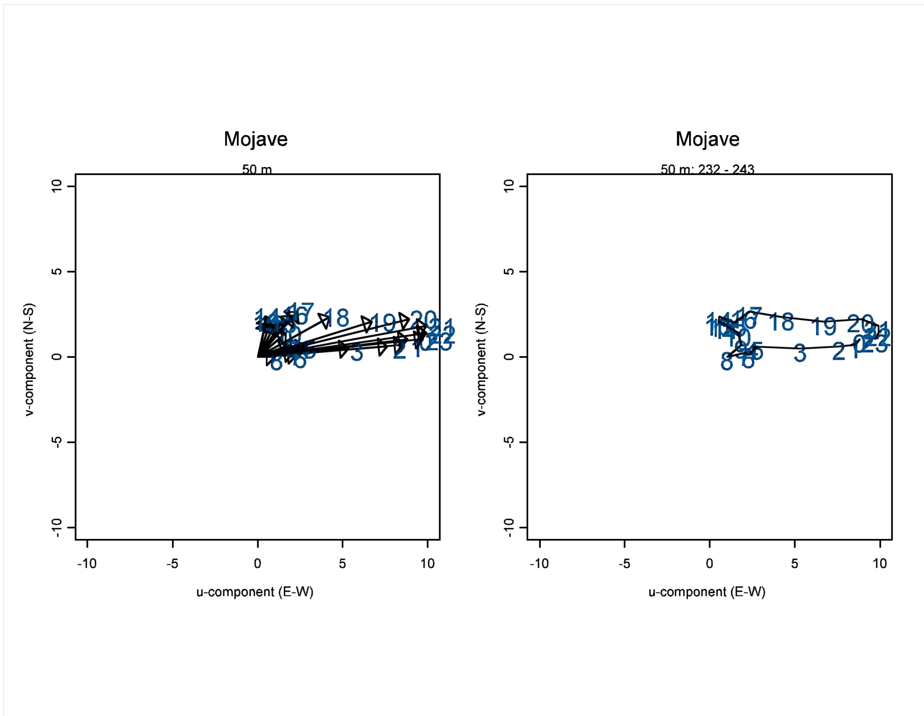


Figure 67: Mojave sodar hodographs, for days 220 to 260.
For the left plot, arrows represent the average wind vector for each hour. The right plot shows the cycle of the mean wind vector by hour of day. Numbers on both plots represent the hour of day.

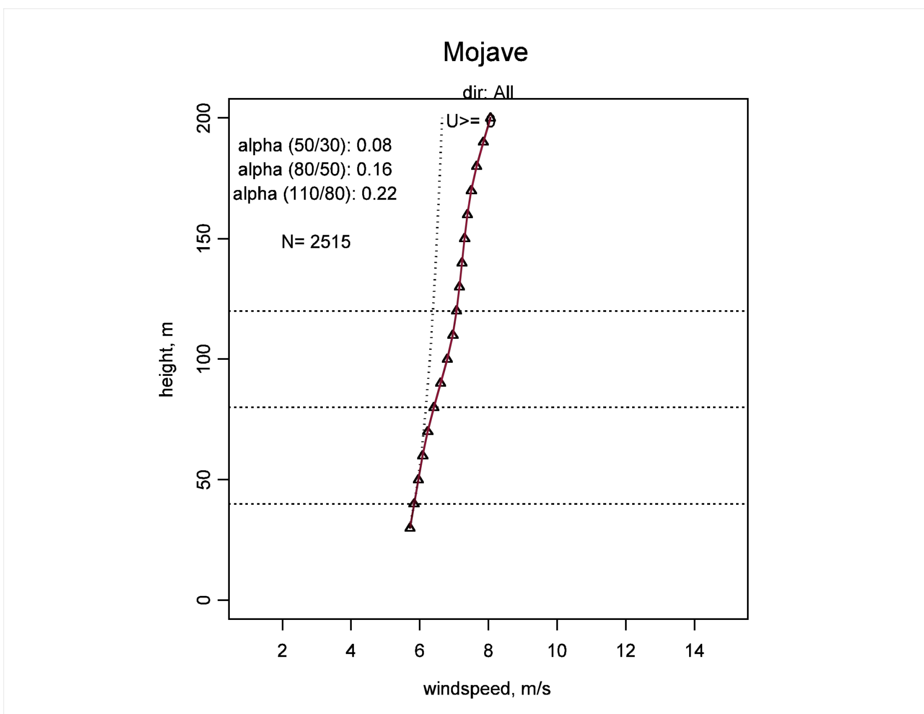


Figure 68: Average wind speed profiles for the Mojave sodar, for all speeds and directions. The dashed line is the extrapolated sodar wind profile using the 50/30 m shear parameter.

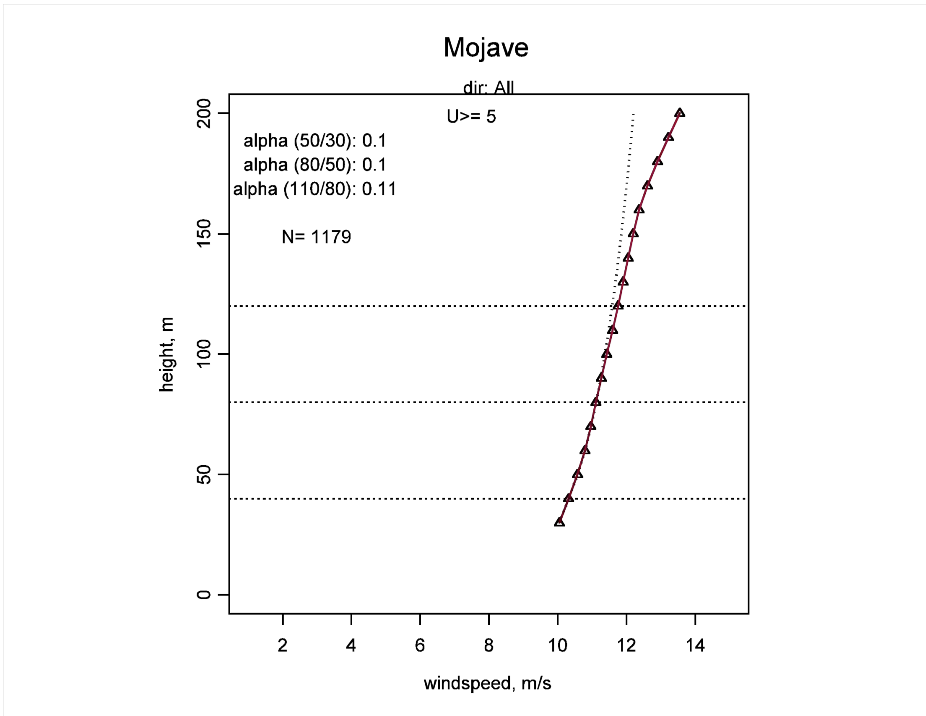


Figure 69: Average wind speed profiles for the Mojave sodar, for all directions, with 50 m speeds ≥ 5 m/s.
The dashed line is the extrapolated sodar wind profile using the 50/30 m shear parameter.

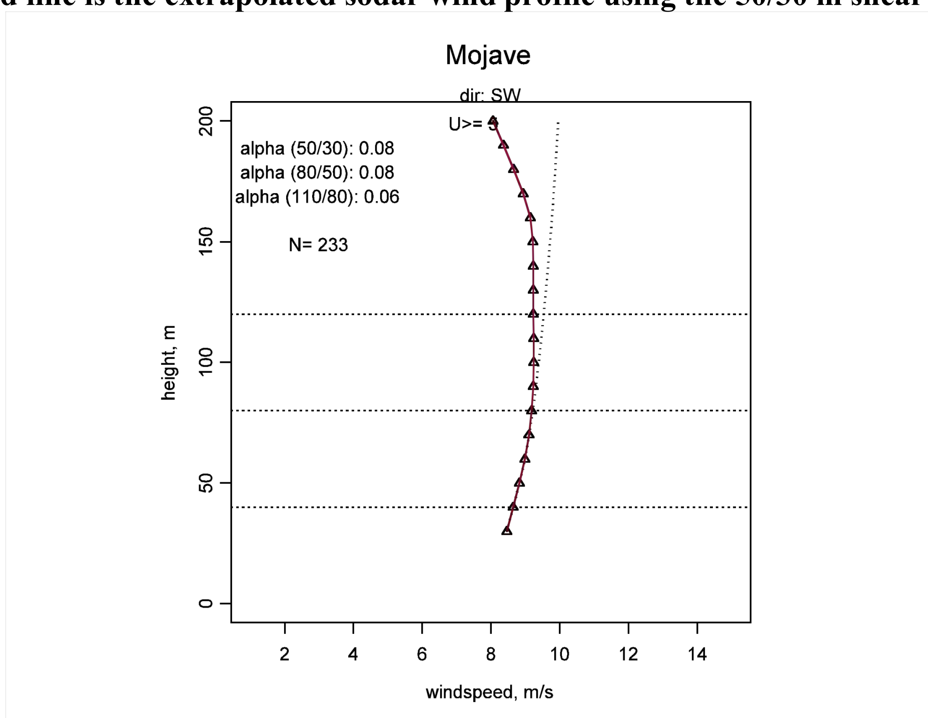


Figure 70: Average wind speed profiles for the Mojave sodar, for 50 m speeds ≥ 5 m/s, and wind from the SW

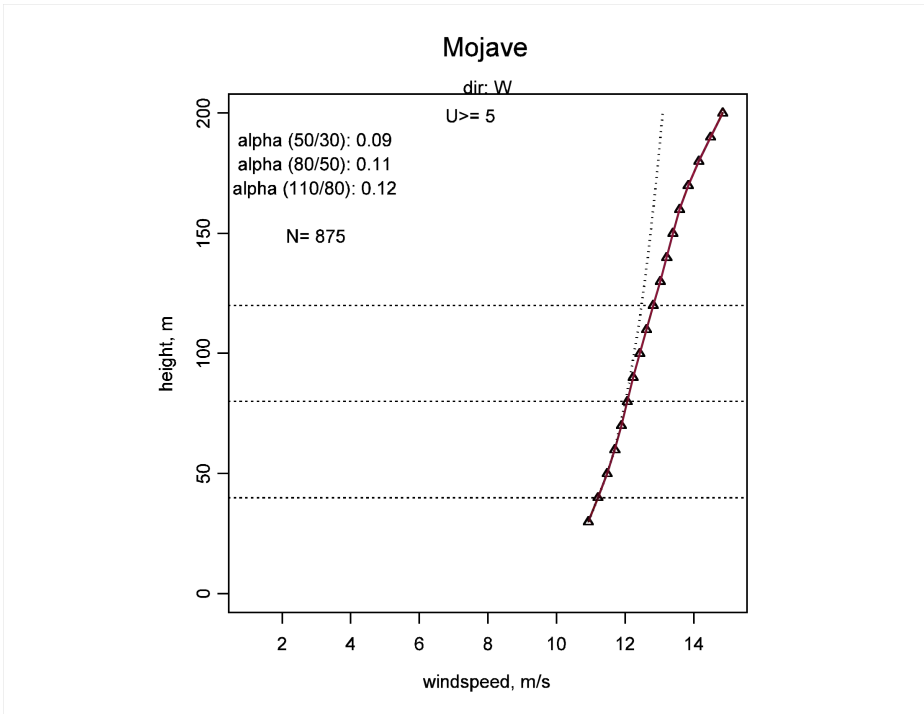


Figure 71: Average wind speed profiles for the Mojave sodar, for 50 m speeds ≥ 5 m/s, and wind from the W

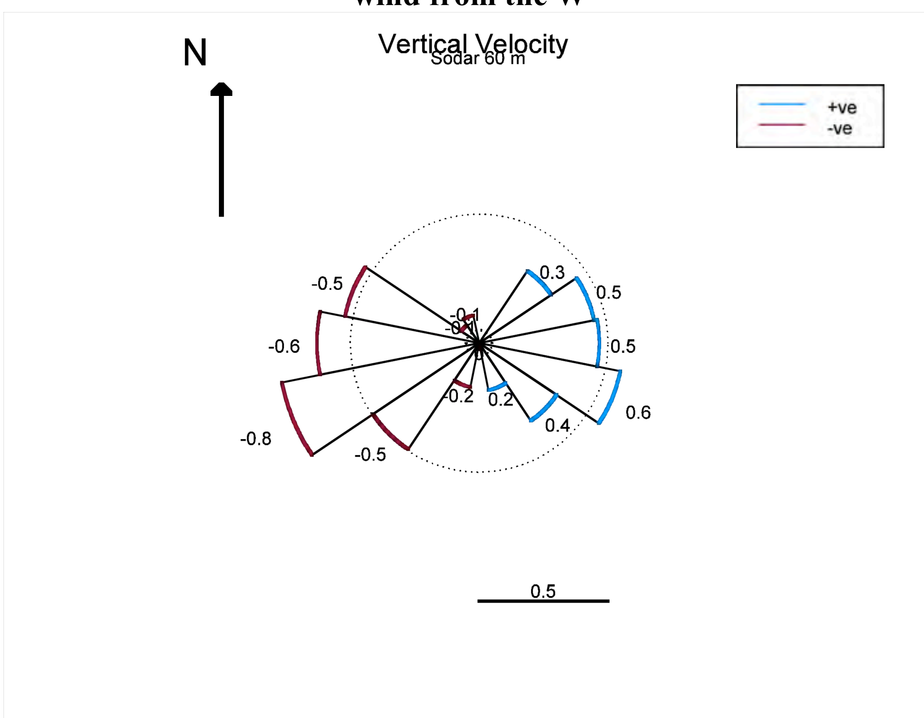


Figure 72: Mojave sodar vertical velocity rose (positive upward)

Figure 73: San Gorgonio sodar site, looking west

Figure 74: San Gorgonio sodar site, looking south

Figure 75: San Gorgonio sodar site, looking north

Table 42: Mean speeds and shear parameters at San Gorgonio by 50 m wind speed. Speed bins are labeled as the lower limit of speed (m/s) for each bin.

Speed	**1**	**2**	**3**	**4**	**5**	**6**	**7**
U@30 m	1.5	2.4	3.5	4.5	5.4	6.3	7.1
U@50 m	1.7	2.6	3.5	4.6	5.5	6.5	7.5
U@80 m	1.7	2.6	3.3	4.3	5.5	6.7	7.9
U@110 m	2.0	2.5	3.0	3.8	5.1	6.4	8.0
U@120 m	2.1	2.5	3.0	3.7	5.1	6.4	8.0
U@140 m	2.5	2.3	2.5	3.5	5.1	6.5	8.0
Shear (50/30 m)	0.14	0.10	0.00	0.01	0.04	0.07	0.12
Shear (80/50 m)	0.05	0.00	-0.13	-0.11	-0.03	0.04	0.10
Shear (110/80 m)	0.48	-0.09	-0.24	-0.42	-0.20	-0.14	0.03
Number of Profiles	23	41	40	49	53	61	118
Speed	**8**	**9**	**10**	**11**	**12**	**13**	**14**
U@30 m	8.0	9.0	9.8	10.8	11.7	12.6	13.7
U@50 m	8.5	9.5	10.5	11.5	12.6	13.5	14.6
U@80 m	8.9	10.0	11.2	12.2	13.4	14.4	15.6
U@110 m	9.0	10.2	11.2	12.5	13.6	14.7	15.9
U@120 m	9.0	10.3	11.3	12.6	13.7	14.7	16.0
U@140 m	9.2	10.2	11.4	12.9	13.9	14.7	16.1
Shear (50/30 m)	0.11	0.11	0.14	0.13	0.14	0.14	0.13
Shear (80/50 m)	0.11	0.12	0.13	0.11	0.13	0.13	0.14
Shear (110/80 m)	0.02	0.07	0.02	0.08	0.06	0.07	0.07
Number of Profiles	141	123	160	202	290	375	419
Speed	**15**	**16**	**17**	**18**	**19**		
U@30 m	14.6	15.3	15.9	16.9	18.1		
U@50 m	15.5	16.4	17.3	18.1	19.2		
U@80 m	16.5	17.2	18.1	18.6	19.8		
U@110 m	16.9	17.5	18.2	18.2	19.8		
U@120 m	17.0	17.6	18.1	18.1	19.8		
U@140 m	17.1	17.4	18.0	17.8	19.9		
Shear (50/30 m)	0.12	0.13	0.15	0.14	0.11		
Shear (80/50 m)	0.13	0.11	0.10	0.05	0.06		
Shear (110/80 m)	0.07	0.06	0.01	-0.07	0.00		
Number of	647	503	194	56	12		

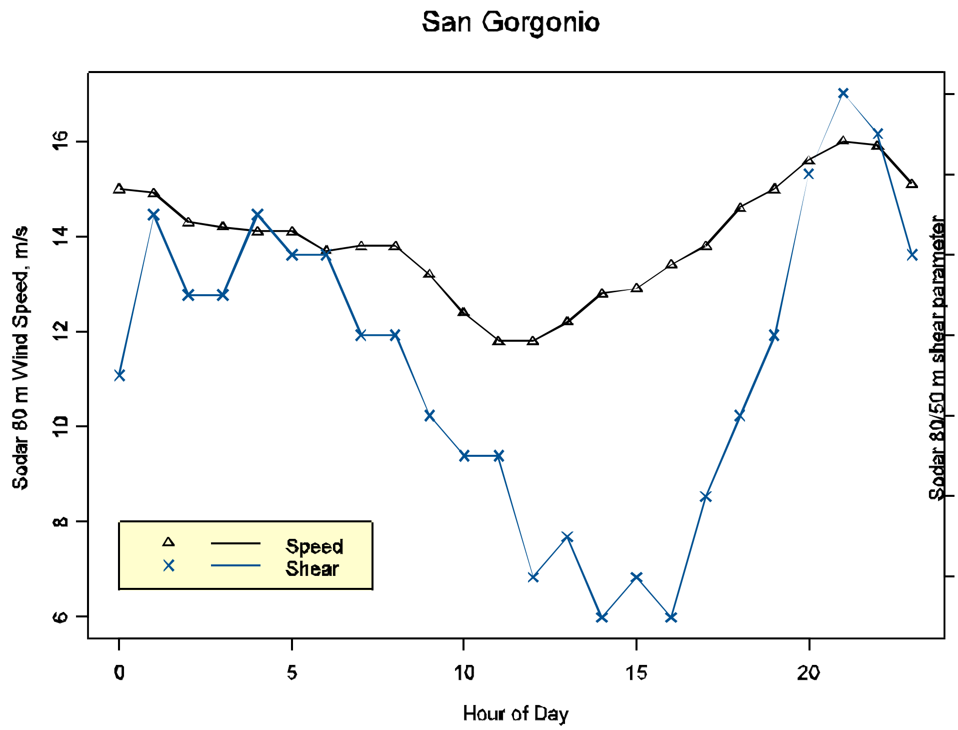


Figure 76: San Gorgonio mean 80 m speed and 80/50 m shear, by hour of day

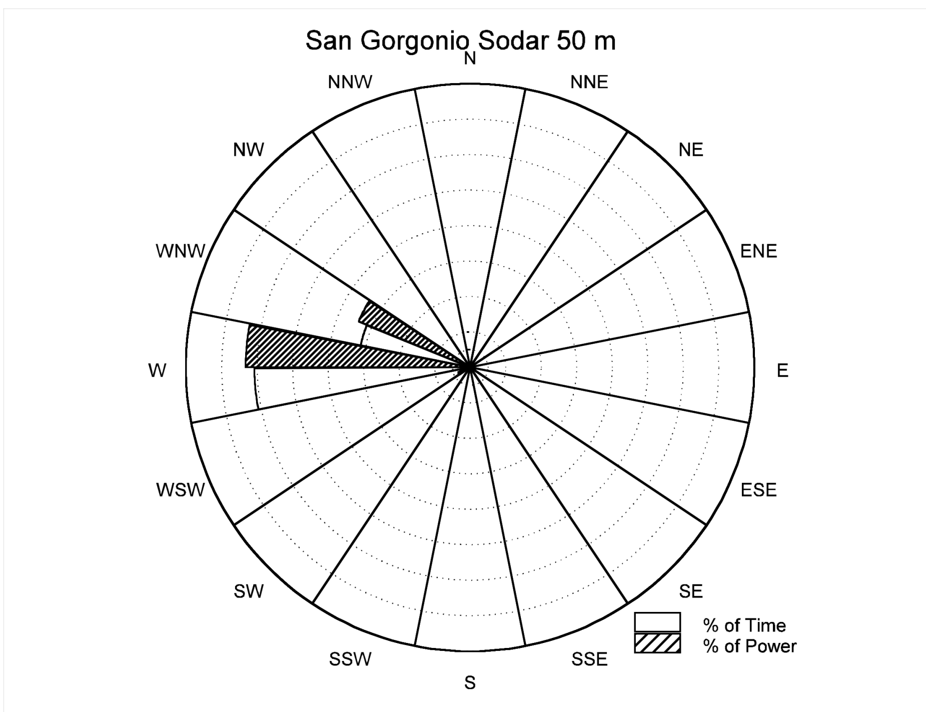


Figure 77: Wind rose for San Gorgonio sodar study.
Dotted circles are at increments of 5% beginning with 0% at the center.

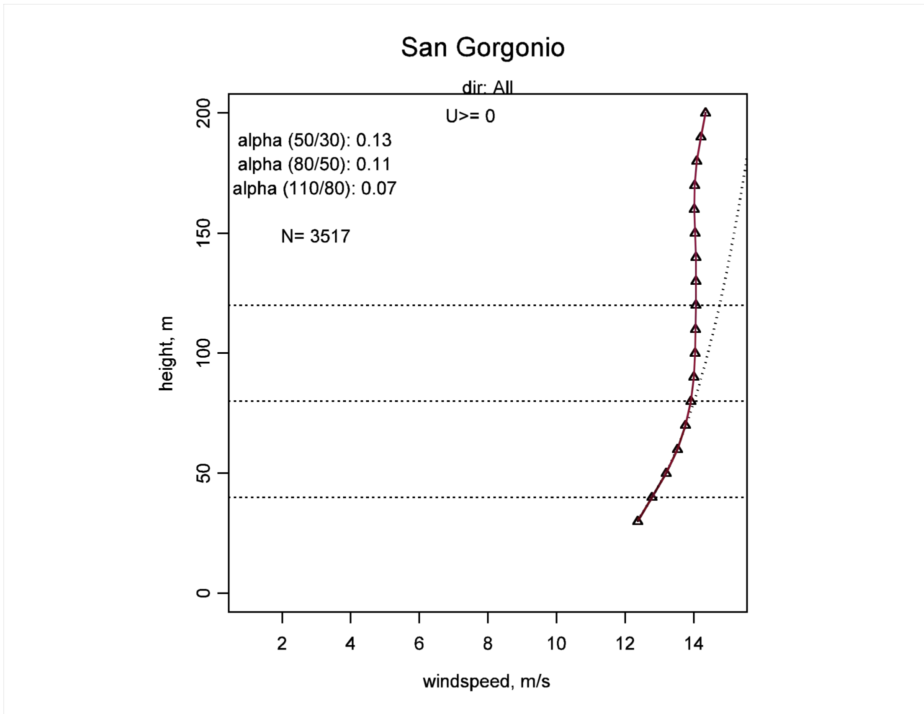


Figure 78: Average wind speed profiles for the San Gorgonio sodar, for all speeds and directions.
The dashed line is the extrapolated sodar wind profile using the 50/30 m shear parameter.

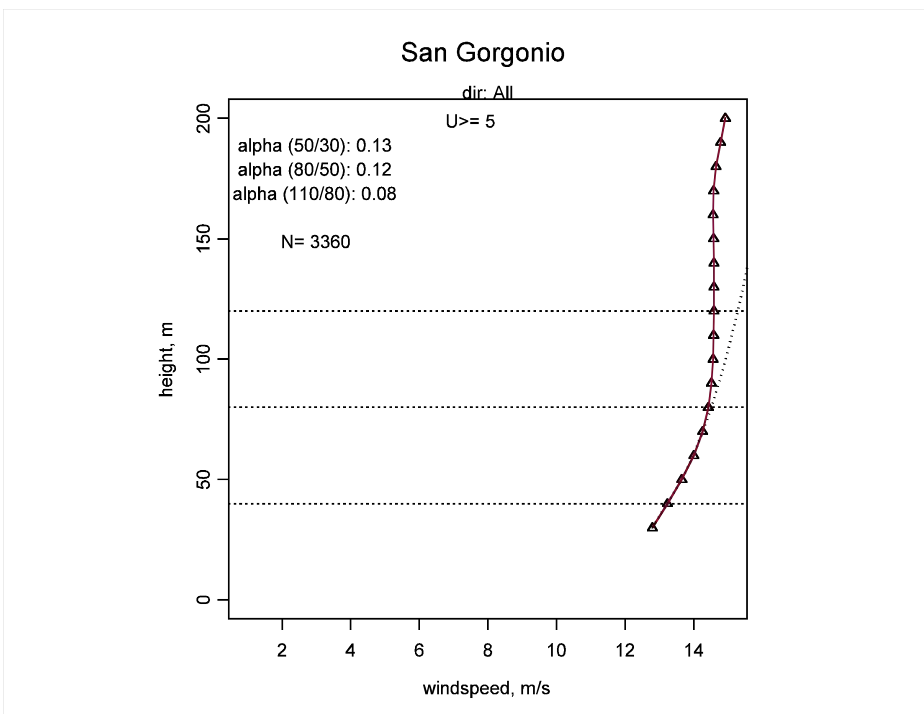


Figure 79: Average wind speed profiles for the San Gorgonio sodar, for all directions, and 50 m sodar speeds ≥ 5 m/s
The dashed line is the extrapolated sodar wind profile using the 50/30 m shear parameter

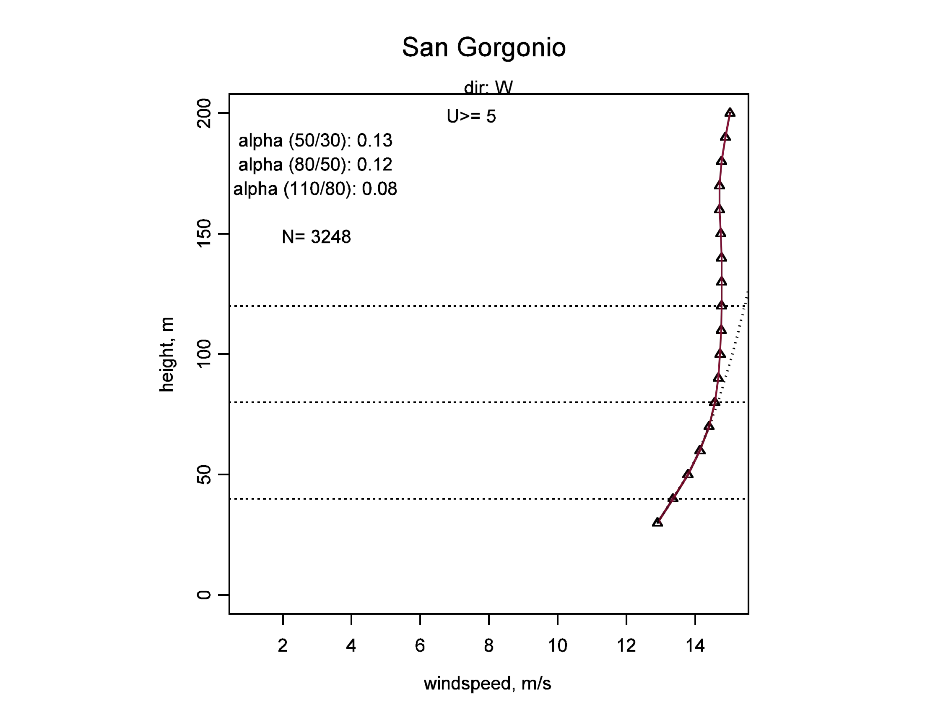


Figure 80: Average wind speed profiles for the San Gorgonio sodar, for 50 m sodar speeds ≥ 5 m/s, and wind from the W

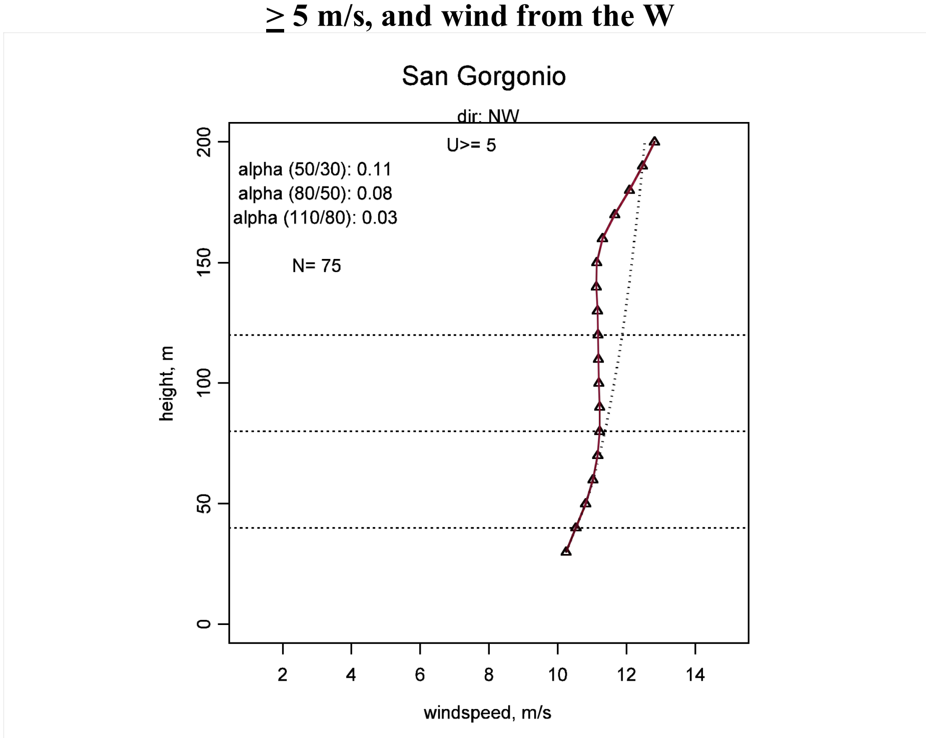


Figure 81: Average wind speed profiles for the San Gorgonio sodar, for 50 m sodar speeds ≥ 5 m/s, and wind from the NW

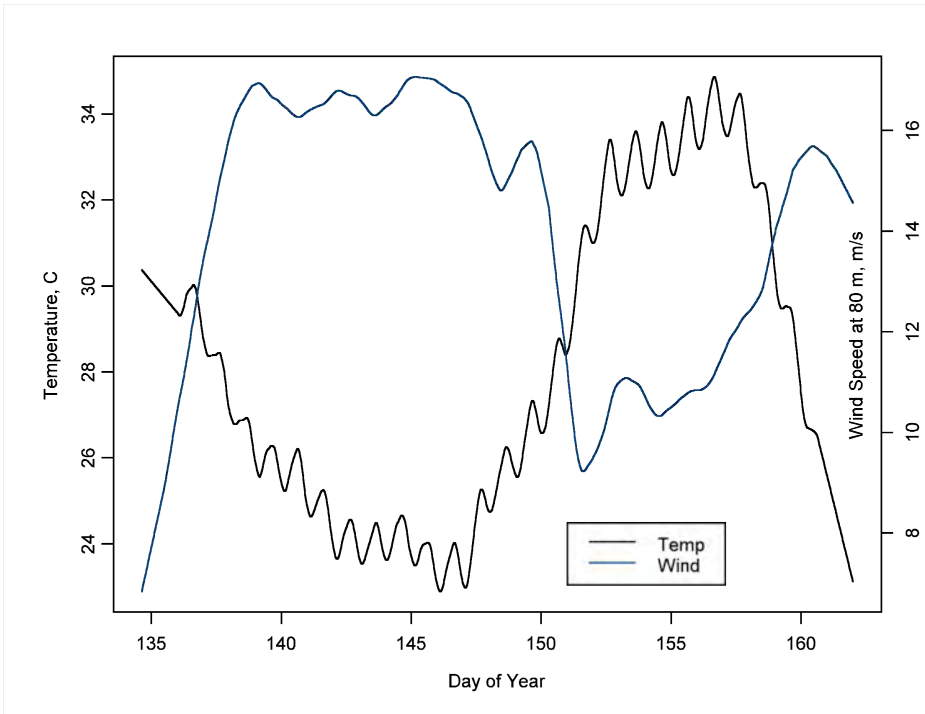


Figure 82: Time series of temperature and San Gorgonio sodar 80 m wind speed. Temperature data from Palm Springs airport. Both temperature data and speed data smoothed to illustrate trends.

Figure 83: Shasta sodar site, looking east

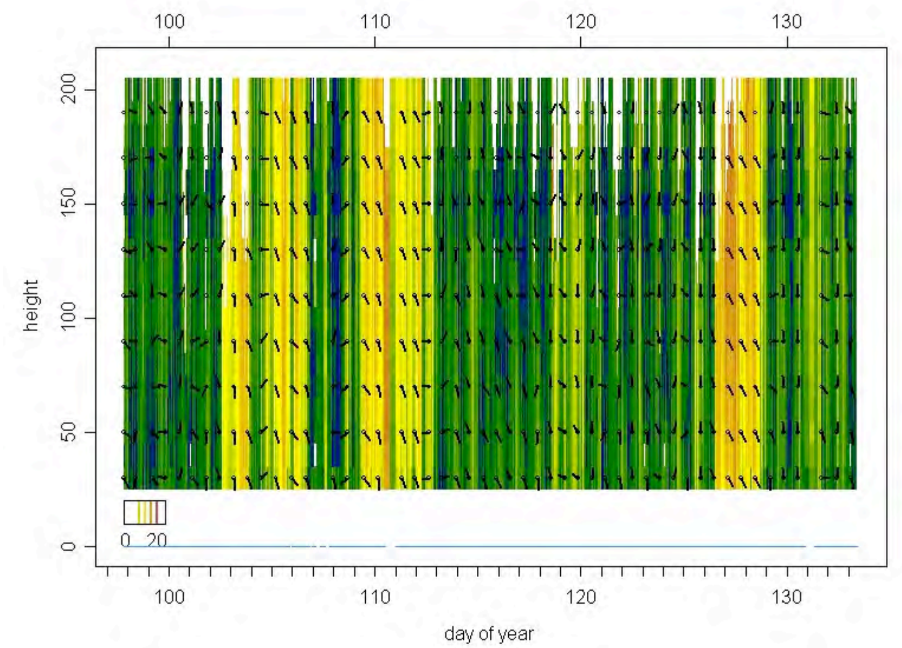


Figure 84: Time-height image of wind speed during the Weed Airport sodar study. Wind direction is indicated by black bars.

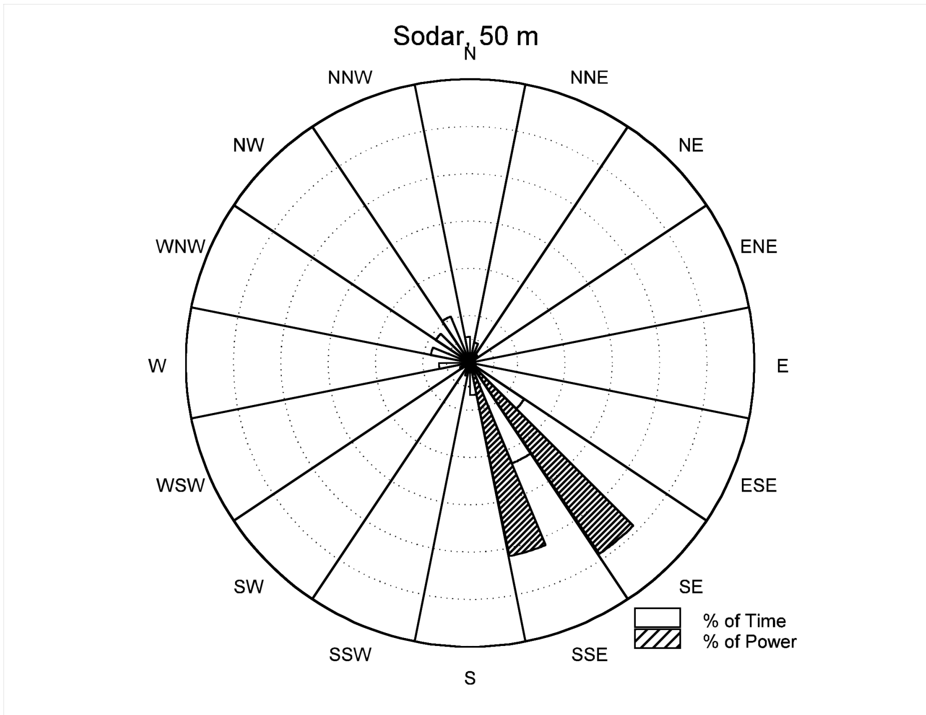


Figure 85: Wind rose for the Shasta sodar study at 50 m.
Dotted circles denote increments of 5%, starting with 0% at the center.

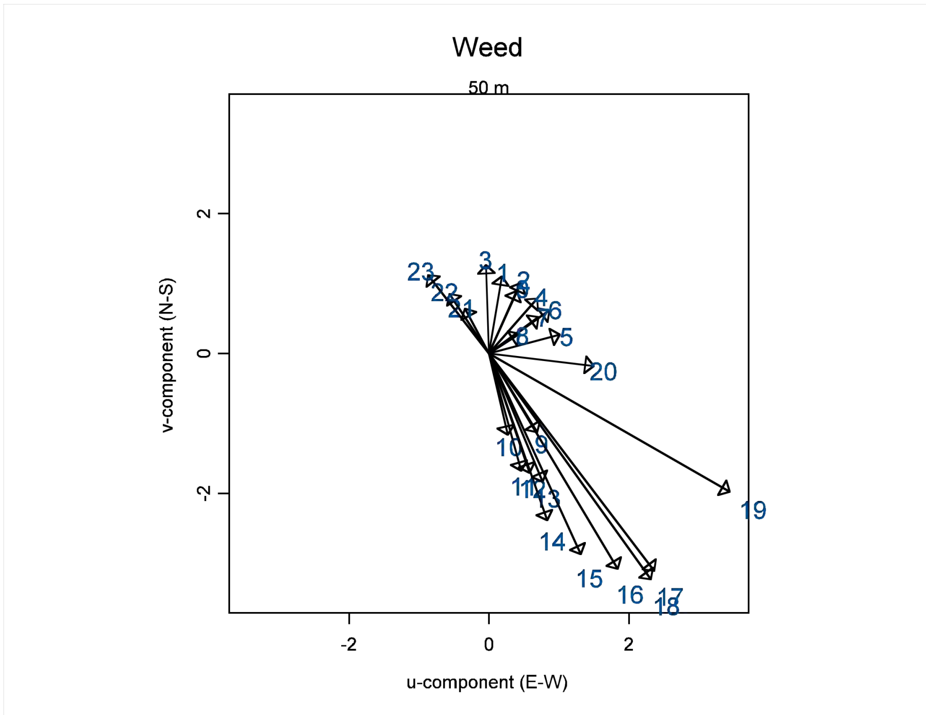


Figure 86: Hourly-averaged wind vectors at 50 m for an undisturbed period (days 113 to 120) at the Weed Airport.
Direction of the arrows gives the wind direction, the length is the vector speed, and the number is the hour of day.

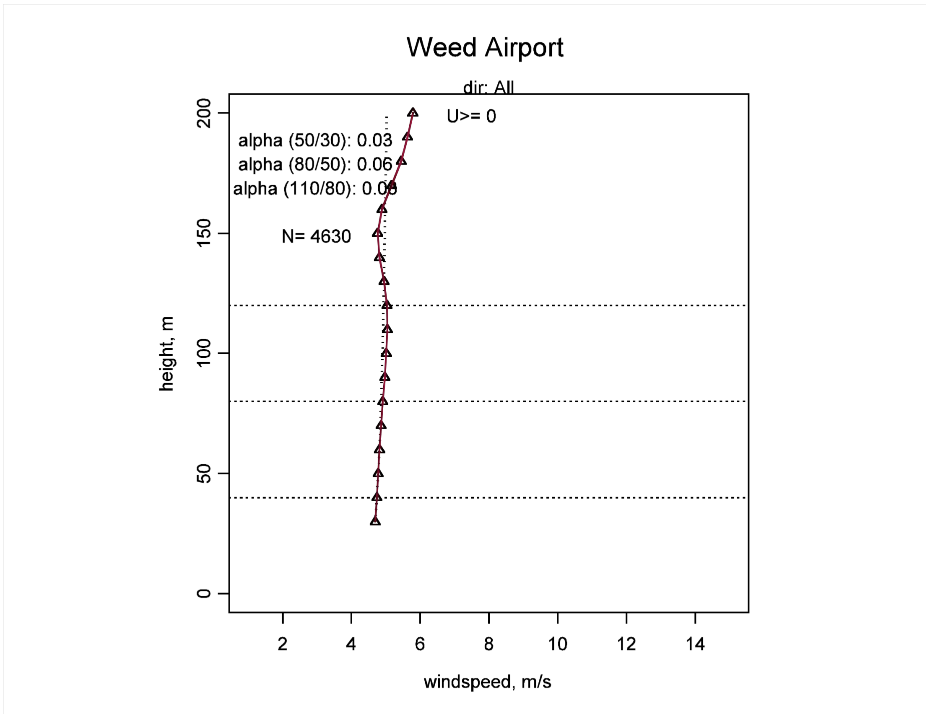


Figure 87: Average wind speed profile during the Shasta sodar study period, for all speeds and directions.
The shear parameters for several layers are also given. "N" is the number of 10-minute observations included.

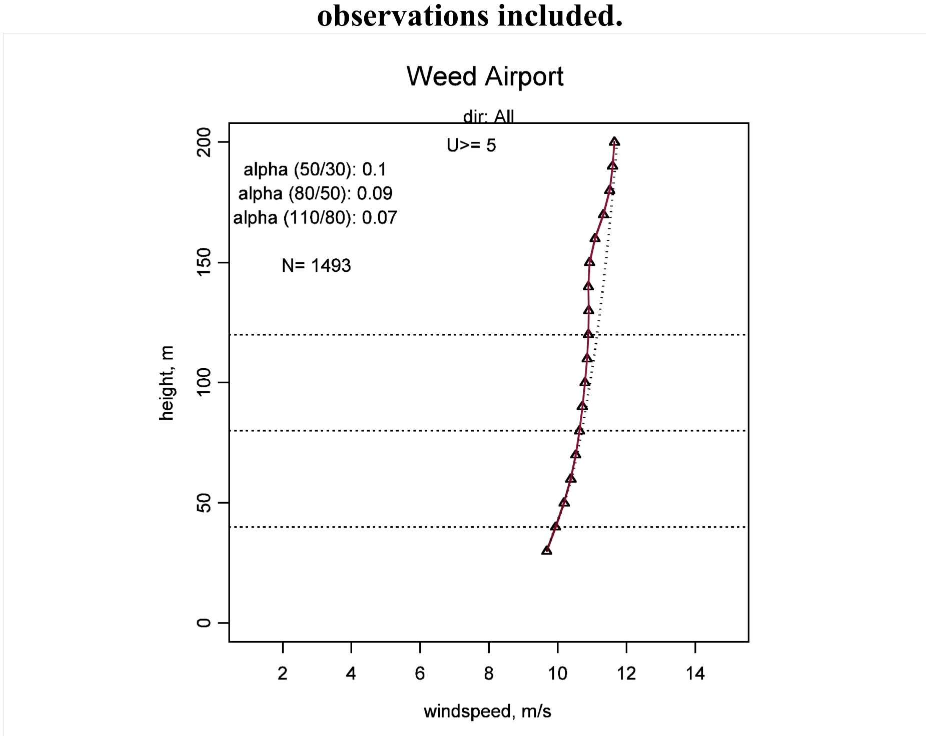


Figure 88: Average wind speed profile during the Shasta sodar study period, for 50 m sodar speeds $\geq$ 5 m/s

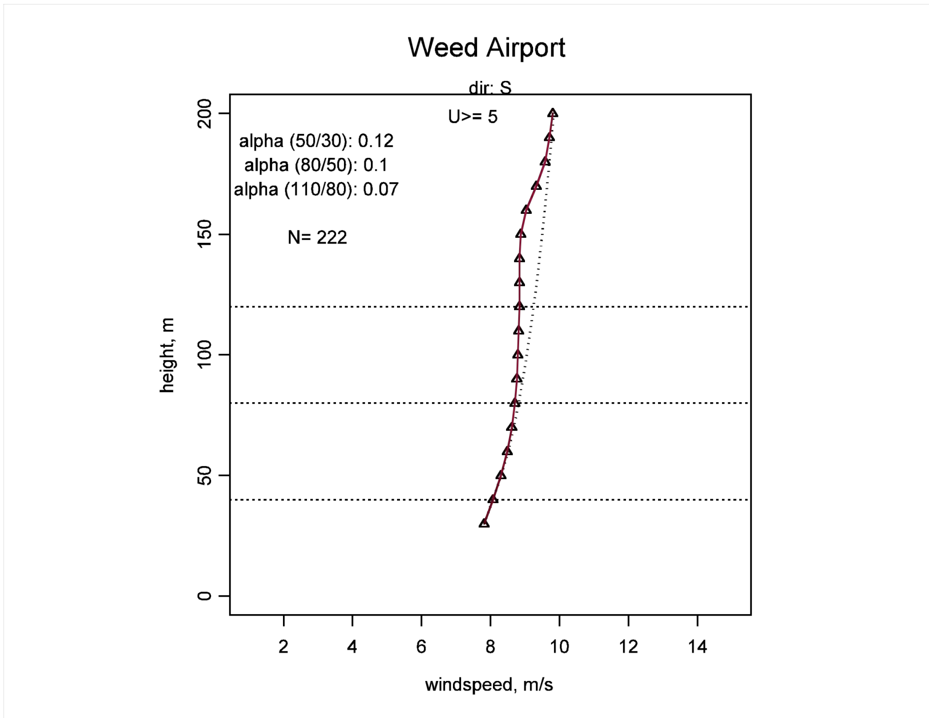


Figure 89: Average wind speed profile during the Shasta sodar study period, for 50 m sodar speeds ≥ 5 m/s and wind from the SE

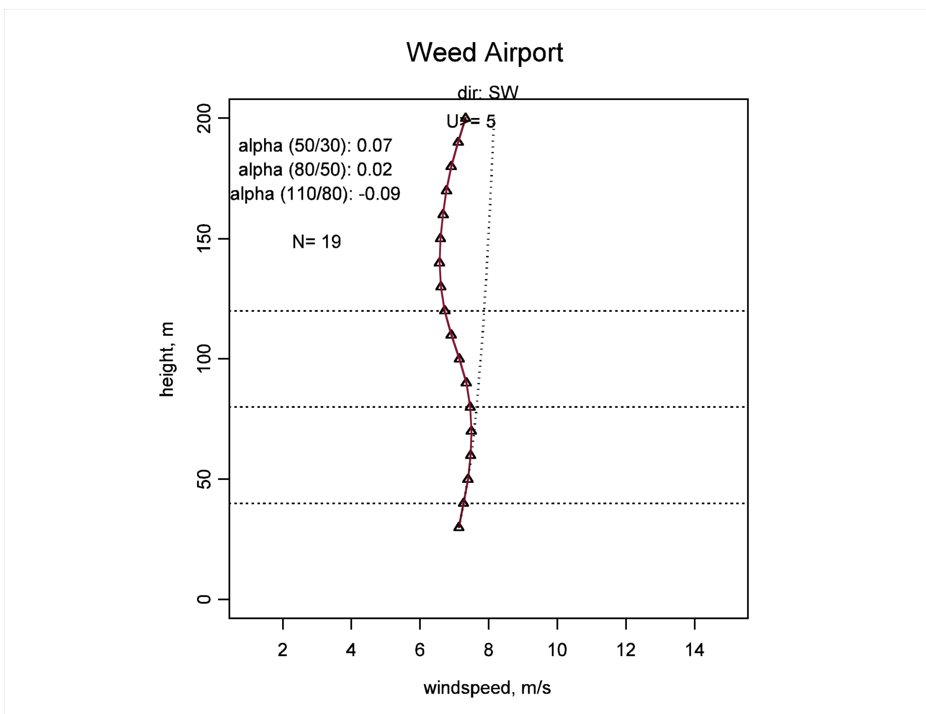


Figure 90: Average wind speed profile during the Shasta sodar study period, for 50 m sodar speeds ≥ 5 m/s and wind from the S

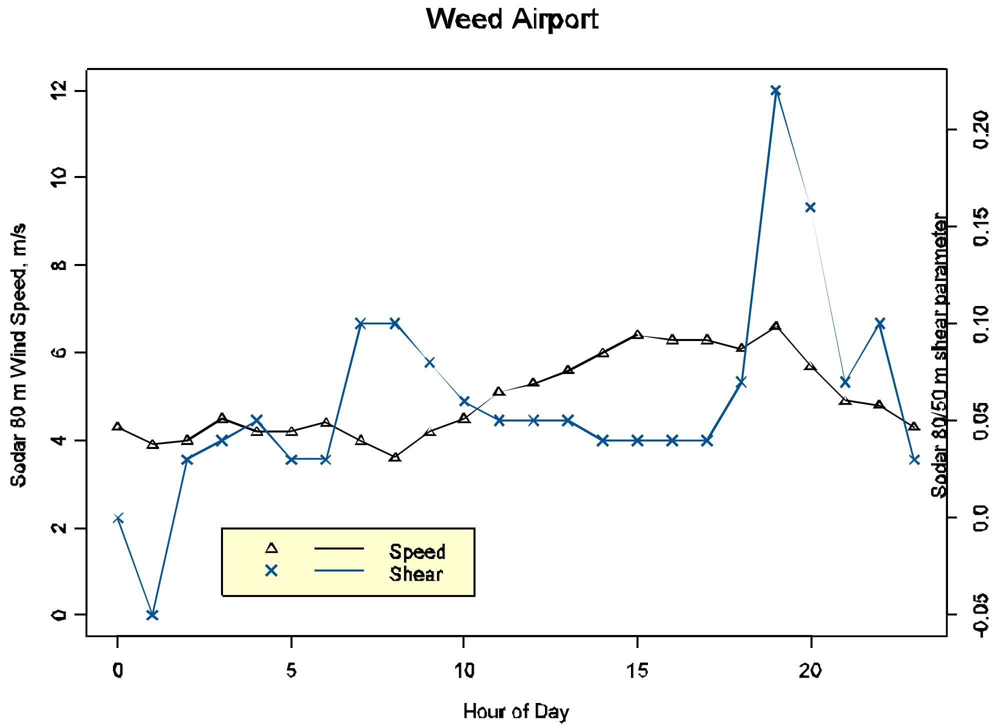


Figure 91: Shasta sodar mean 80 m speed and 80/50 m shear, by hour of day

Figure 92: Meteorological station operated by the California Department of Water Resources, located at the Weed, CA airport

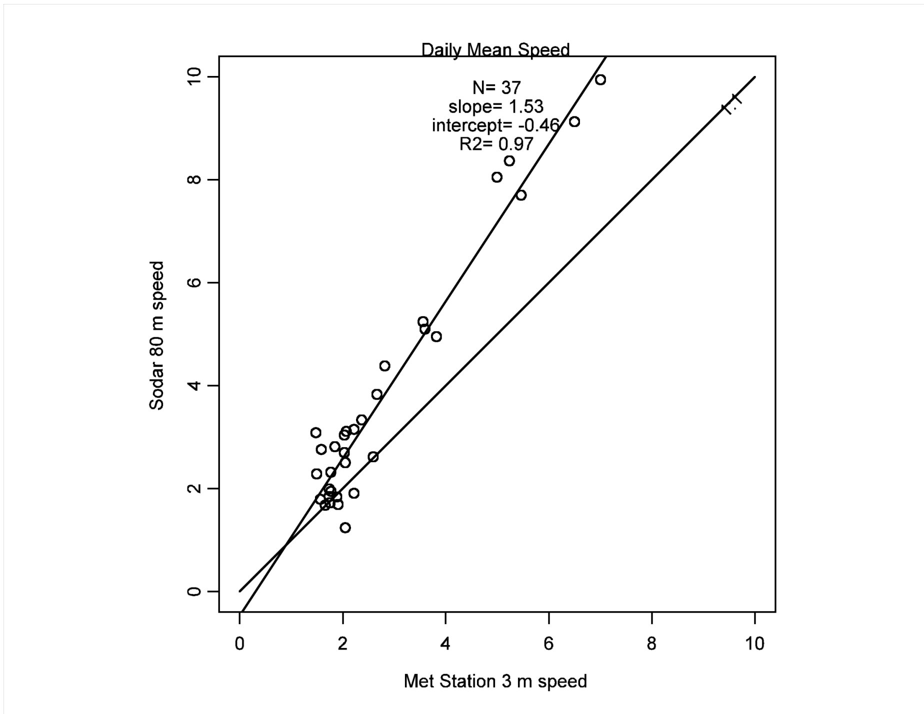


Figure 93: Comparison of sodar 80 m daily mean speeds (m/s) with the Weed Airport met station speeds

Table 43: Shasta sodar mean speeds ("U") and shear parameters at specified heights (m) by 50 m speed bin.
Bin designations are by the lowest speed in the bin.

Speed	0	1	2	3	4	5	6	7	8
U@30 m	0.8	1.7	2.5	3.4	4.4	5.3	6.1	7.0	8.0
U@50 m	0.7	1.5	2.4	3.4	4.4	5.4	6.5	7.5	8.5
U@80 m	1.1	1.5	2.3	3.3	4.4	5.5	6.9	7.9	8.8
U@110 m	1.5	1.6	2.3	3.2	4.2	5.3	6.9	8.1	9.0
U@120 m	1.5	1.6	2.2	3.1	4.1	5.2	6.9	8.1	9.0
U@140 m	1.3	1.5	2.0	2.7	3.5	4.8	6.5	7.9	9.1
Shear (50/30 m)	-0.09	-0.19	-0.07	-0.01	0.03	0.05	0.13	0.13	0.11
Shear (80/50 m)	0.91	-0.05	-0.13	-0.09	-0.01	0.02	0.11	0.11	0.09
Shear (110/80 m)	0.97	0.27	-0.03	-0.07	-0.15	-0.09	0.03	0.08	0.05
Number of Profiles	475	1047	841	469	284	177	138	140	144
Speed	9	10	11	12	13	14	15	16	17
U@30 m	9.0	9.9	10.9	11.9	13.0	13.8	14.8	15.8	16.8
U@50 m	9.5	10.4	11.5	12.5	13.5	14.4	15.4	16.4	17.3
U@80 m	10.0	11.0	12.1	13.2	14.0	15.0	16.0	16.7	17.6
U@110 m	10.5	11.4	12.5	13.4	14.3	15.3	16.3	16.8	17.8
U@120 m	10.6	11.5	12.6	13.5	14.3	15.4	16.3	16.8	17.8
U@140 m	10.7	11.6	12.7	13.6	14.4	15.8	16.5	17.0	18.2
Shear (50/30 m)	0.12	0.11	0.10	0.11	0.08	0.09	0.08	0.07	0.06
Shear (80/50 m)	0.11	0.10	0.11	0.10	0.08	0.08	0.08	0.04	0.04
Shear (110/80 m)	0.14	0.11	0.10	0.07	0.06	0.06	0.05	0.02	0.02
Number of Profiles	169	170	118	126	106	105	78	29	10